Pre-Phase A Study for the Australian Development of a Satellite Cross-Calibration Radiometer (SCR) Series Including Potential to Support Partner Land Imaging Programs

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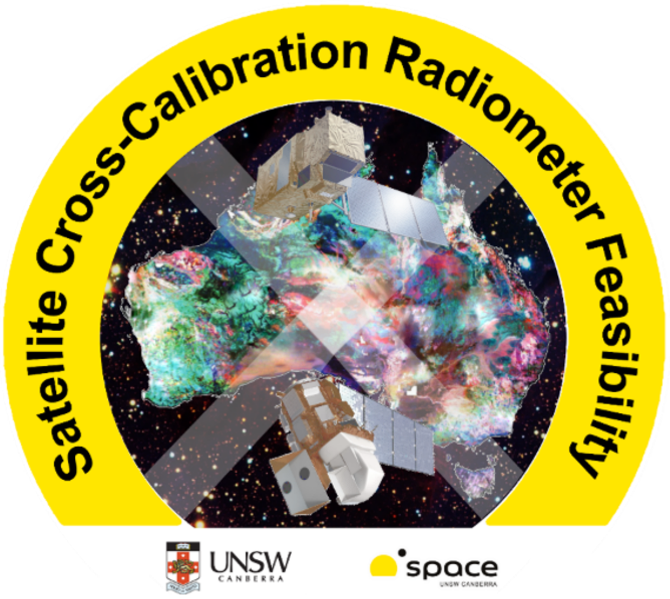

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1 Executive brief

- This document presents the results of a pre-phase A study for an Australian Satellite Cross-Calibration Radiometer mission following NASA system engineering standards.
- The **Satellite Cross-Calibration Radiometer (SCR) mission** provides:
    - a stable and accurate reference that improves the radiometric image quality of Earth observation systems to 1-2%, including from the missions of our major EO data supply partners in the USA and Europe.
    - an opportunity to secure Australia's data supply for Earth observations.
    - Considerable economic and societal benefits arising from improved confidence in Earth observation satellites utilised by Australia and partners worldwide.
    - a pathway to develop the Australian space sector, including manufacturing.
- This work represents the second release of the **12th study conducted at UNSW Canberra Space's Australian National Concurrent Design Facility** and was performed with support from Geoscience Australia, the Australian Space Agency and CSIRO.
- From December 2020 to August 2021 a total of 74 individuals from 21 organisations were consulted or participated in the study.
- The NASA/USGS (National Aeronautics and Space Administration/United States Geological Survey) Landsat programme provides a critical dataset to Australia. Australian users are also making increasing use of this data alongside data from foreign government programs and commercial operators. This study explores opportunities for uplifting Australian capability and contributing to the US land imaging program while improving calibration of optical satellite.
- The study found the **SCR mission is technically and programmatically feasible**. While no Commercial off the Shelf (COTS) option exists for the whole system, a combination of custom and COTS selected elements can be provided mainly from within the Australia space sector.
- Opportunity exists to maximise outcomes of the SCR pathfinder mission by aligning to the timelines of NASA's CLARREO Pathfinder mission which launches at the end of 2023. However, the mission will still deliver the intended effects if this is not possible. To align with CLARREO, the SCR pathfinder missions would need to be initiated within 2021.
- The study identified four specific satellite systems required for the mission which are not COTS products today . Development of these systems represent an opportunity for Australia to develop the capabilities to support an SCR mission and hold export potential.
- The study identified a development approach that would occur in two distinct stages:
    - Stage 1: delivering the **satellite cross-calibration** series. The **space elements to design, build, launch and operate a single SCR satellite would cost approximately AUD 36M**, in the 25-100kg weight class and take ~2 years to develop.
    - Stage 2: following the successful delivery of four satellite cross-calibration missions, transitioning to a **multi-mission hyperspectral smallsat** series (Multi-mission Imager – MMI) incorporating the requirements for bushfire fuel monitoring via the OzFuel mission and water quality monitoring via the AquaWatch mission. The **space elements to design, build, launch and operate a single multi-mission satellite would cost approximately AUD 75M –AUD 100M**, in the 75-250kg weight class and take ~2-3years to develop.
- Both phases would include **launch of two satellites every two years**, subject to ongoing funding. In addition to contract management functions, the **mission owner would undertake ground station operations, maintain ground calibration networks and utilisation activities like data processing and distribution,** outside of the above costing.
- One of the key outcomes for Australia's investment in the SCR mission is the associated development of domestic space industry capability and involvement of domestic organisations in the project.
- UNSW Canberra Space assesses the SCR mission is ready for phases A and B mission development analysis in addition to informing the Australian Space Agency's Earth Observations from Space Technology Roadmap.

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5 Executive summary

Australia is currently one of the largest users of satellite Earth Observation (EO) data worldwide, with these data coming from foreign governments and the private sector. Our access to these data is negotiated through partnership agreements, with Australia working to support the objectives of our partners and help them achieve efficiencies in their programmes. Australia's continued access, or 'securing data supply', under these partnerships are assessed as being at moderate to high risk and require urgent attention.[1]

The *2016 Australian Earth Observation Community Plan 2026* highlights the need for Australia to be an essential component of the international EO capability, delivering benefits to the international community and securing our access to, and involvement in, international EO programmes.

The **Australian Satellite Cross-Calibration Radiometer (SCR) series** of hyperspectral sensors aims to directly improve the calibration of the smaller optical satellites increasingly used in the commercial Earth observation sector to deliver more interoperable data. These data quality improvements are achieved through cross-calibration – quantification of the differences in data signals received at the top of the atmosphere – of different Earth observation satellites. In effect, this means that data from one satellite can be combined with data from other satellites to increase their overall utility. Also, increases in the radiometric accuracy of optical satellite Earth Observation Analysis Ready Data (ARD) from 3% to 1% are expected and this translates to the ability of identifying a specific crop as opposed to merely identifying generic agricultural activity.

SCR would secure Australian data supply by

- contributing to the global observing system,
- strengthening relationships with other space fairing nations, and
- contributing to the goals set out in the *Australian Civil Space Strategy 2019-2028*[2].

The SCR program would seek an ongoing funding stream that will build Australia's space manufacturing base through long term space mission funding and the subsequent realization of flight heritage. This will enable Australian-owned, controlled and operated entities to compete on the global stage for space mission opportunities and will cement Australia's goal of tripling the Australian industry market size to $12 billion and the addition of 20,000 jobs by 2030.

This study was conducted by UNSW Canberra Space with support from Geoscience Australia (GA), the Australian Space Agency (The Agency), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the United States Geological Survey (USGS). It applied a concurrent engineering methodology aiming to align objectives to the NASA systems engineering approach (defined in section 6) to derive a space mission feasibility assessment and programmatic cost estimation. The core study team comprised 11 experts from across the engineering and space sectors plus additional support. In total, the study involved a total of 74 individuals from 21 organisation worldwide.

SCR satellites would be launched into orbits where they would provide coincident imagery opportunities with several **highly calibrated Earth Observation missions** such as the NASA/USGS Landsat, EC (European Commission) Sentinel or Planet's SuperDove series. By performing coincident, hyperspectral observations, they provide highly accurate and stable cross-calibration data to targeted cooperative missions that have lower radiometric accuracy.

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[1] Australian Earth Observation Community Coordinating Group (2016), Australian Earth Observation Community Plan 2026: Delivering essential information and services for Australia's future, p. 13.

[2] Australian Space Agency (2019), Advancing Space: Australian Civil Space Strategy 2019-2028, https://publications.industry.gov.au/publications/advancing-space-australian-civil-space-strategy-2019-2028.pdf, accessed 14/01/2021

The **SCR series would involve launch of 2 satellites every 2 years, starting with a pair of pathfinder missions** in Q4 2023, and followed by the full operational capability (FOC) as of Q4 2025 as depicted in Figure 1.

Following FOC, two stages were identified:

- Stage A delivers the satellite cross-calibration series.
- Stage B delivers the satellite cross-calibration series then transitions to a Multi-mission Imager (MMI) which is a hyperspectral instrument deployed on a smallsat series incorporating requirements from CSIRO and SmartSat CRC's AquaWatch mission[3]- in addition to ANU's OzFuel[4] following launches three and four

The pathfinder missions, while technically aligned, pursue complementary purposes:

- **SCR 1 is a low-risk version** relying on COTS systems to facilitate a launch at the same time as NASA's CLARREO-Pathfinder mission in Q4 2023. SCR 1 would be designated a NASA Class D mission (meaning moderate to low complexity and cost, and high-risk tolerance) - to meet the aggressive development schedule.
- **SCR 2 is an opportunity for Australian industry** to ramp up its manufacturing capability and provide significant Australian content. SCR 2 would also be designated as a NASA Class D mission.

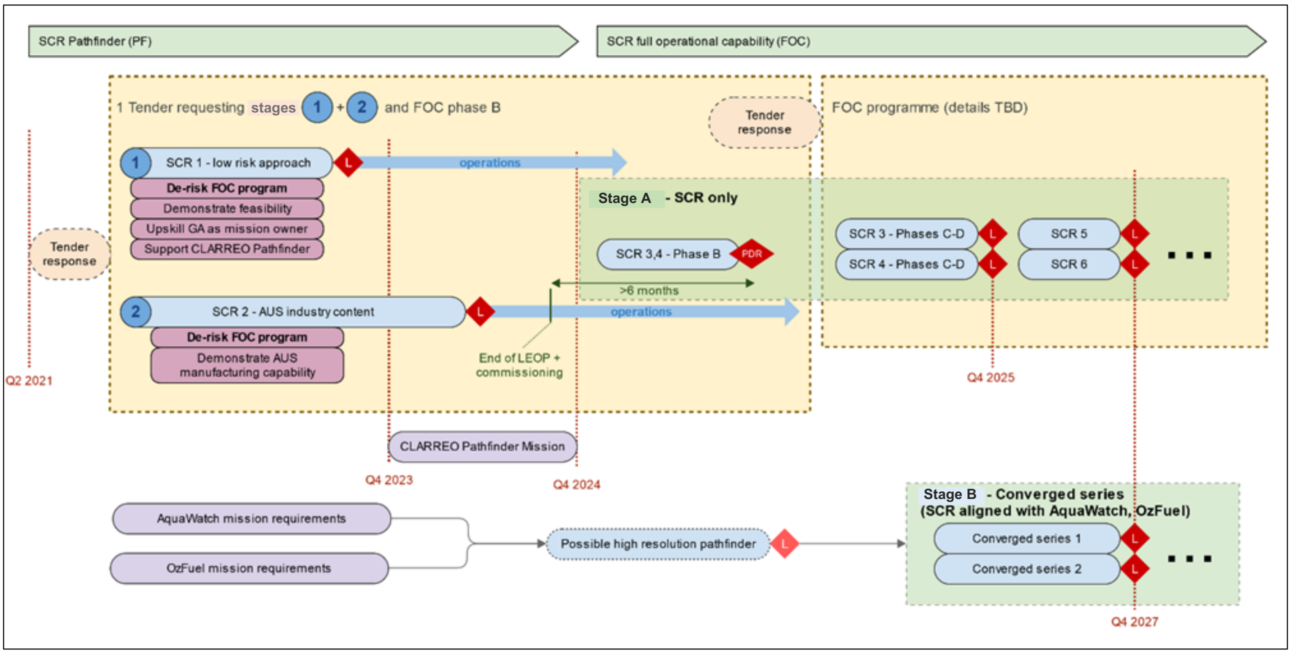

Figure 1 SCR programme overview (for detailed description refer to section 9.4)

The USGS developed the preliminary SCR specification and conducted a background requirements analysis. This concurrent design engineering study examines the Australian capability to design a system that implements the USGS requirements. During the study, mission observation requirements were derived to meet the needs of the user community working with SCR data and deliver a technical concept that is feasible for the current and expected Australian space

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[3] https://smartsatcrc.com/projects/next-generation-earth-observation-data-services/phase-0-aquawatch-australia/
[4] https://www.anu.edu.au/news/all-news/anu-optus-bushfire-research-centre-of-excellence

manufacturing capability. For most parameters, these requirements align with those publicly presented by USGS in 2019[5].

The **primary instrument** to achieve those observation requirements would be a **hyperspectral, imaging spectrometer**. While this is not new technology, the primary technical challenge is to achieve the precise radiometric accuracy required for the mission concept. Consequently, it is expected that **instrument calibration could be a key area of collaboration with potential partners like USGS or NASA** calibration facilities and experts.

The large amounts of data generated by SCR means a network of ground stations is needed, presenting a second area of international collaboration.

Four technological elements have been identified as opportunities for immediate de-risking and local manufacturing capability increase:

- A **hyperspectral instrument** meeting the SCR observation and size requirements
- An **on-board calibration subsystem** for hyperspectral small satellites
- A **payload data handling subsystem** capable of handling data rates of at least 200Mbps and of simultaneously writing to and reading from mass memory
- An **X-band antenna and radio** for small satellites capable of transferring data with at least 250Mbps to existing ground stations

In addition, several open technical questions have been identified that require further assessment in future design phases. (see section 12 for details)

The mission cost has been derived using two independent methodologies. A bottom-up costing approach estimated ROM costs for each mission element and summed them to obtain a **total contracted cost of AUD 36M including design, build, launch and flying a single SCR mission** (see section 10.1 for details). The bottom-up costing was informed by a desktop study of recent satellites and a focused Request for Information (RFI) activity (see section 11.6.3.1 and 11.6.3.2 respectively for details). In parallel, a parametric satellite mission cost model has been applied and supports the above cost figure. This model has been calibrated to the Australian market context by comparing its results to actual costs of two recent Australian satellite missions.

The Multi-mission Imager (MMI) system development costs have been estimated using inputs and results from this study, by comparing the costs to develop science grade HSIS such as EnMap and PRISMA as well as knowledge of high-performance EO instruments which are similar in complexity to a Multi-mission system. A cost comparison was also made with the estimated costs of other Australian mission concepts namely AquaWatch and OzFuel.

The Multi-mission spacecraft is highly likely to be a 75-250 kg smallsat which will provide the required pointing, mechanical and thermal stability and station keeping capability. The provisional cost estimate for the **MMI system is AUD 75-100M**. More work is needed to codify the mission and space segment requirements and perform a detailed concept design to refine this estimate. This would be a goal of a future Phase A study.

The **mission owner would be the Australian government and it would be responsible for project management, tender evaluation, contract management, ground station operations, ground calibration, facilitating data utilisation and engagement activities**.

- The large data volumes being downloaded from SCR would require a network of ground stations. This ground station network could comprise combinations of existing Australian and partner government stations, commercial stations, and new build stations at new sites.

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[5] *Christopherson, J., JACIE 2019,* https://calval.cr.usgs.gov/apps/sites/default/files/jacie/Christopherson-Need-for-an-On-Orbit-Gold-Standard.pdf

- As SCR’s primary mission is calibration, ground calibration requirements are considerably higher than a traditional mission require many existing sites and new sites in addition to considerable on-orbit calibration.
- The mission owner would also facilitate data utilisation activities including data processing from Level 0 to Level 3 products, high availability global data distribution and data archiving.
- Engagement activities such as with Australian space education facilities.

A key schedule driver is parallel operation of SCR 1 with the NASA CLARREO-Pathfinder mission, currently expected in Q4 2023, if possible. Assuming 18 months is needed to develop the mission and 3 months is needed for on-orbit commissioning, procurement would need to begin in late 2021. However, if this alignment is not possible, all SCR elements remain useful and desirable for the reasons outlined above.

As part of the study, a preliminary risk assessment has identified key programme risks and applicable mitigation strategies (Section 11.1.7). The most critical risks can be mitigated through the establishment of international best-practice systems engineering and procurement processes by the mission owner. For these reasons, while the SCR mission could be undertaken by Australia alone, partnership with an experienced space agency would be highly desirable.

If the mission proceeds to further design cycles, UNSW Canberra Space provides a pathway to phase A/B space mission analysis.

The **SCR mission informs the Australian Space Agency’s Earth Observations from Space Technology Roadmap** (“the Roadmap”) being developed by The Agency, in close partnership with the Bureau of Meteorology, CSIRO, the Department of Defence, Geoscience Australia and the Australian Earth observation community.

6 Study context

To examine the technical feasibility of the SCR mission, this study has adopted the mission concept and preliminary requirements developed by USGS and NASA.

The study is consistent with the NASA definition of a phase A design study[6].

Table 1 NASA definition of space mission pre-phase A

Pre-Phase A	Concept and Technology Development
Purpose	To determine the feasibility and desirability of a suggested new system and establish an initial baseline compatibility with NASA's strategic plans. Develop final mission concept, system-level requirements, needed system technology developments, and program/project technical management plans.
Typical outcomes	System concept definition in the form of simulations, analysis, engineering models and mock-ups, and trade study definition

This is with two clear exceptions:

1. Formal Pre-Phase A design reviews including Mission Concept Review (MCR) and System Requirements Review (SRR) have **not** been undertaken; and
2. Baseline plans outside this document have **not** been generated. In future phases of a program, these could include as a minimum (and in keeping with a Class D program): a Program Management Plan (PMP), WBS and Product Tree, Systems Engineering Management Plan (SEMP), Risk Management Plan (RMP), Master Schedule, Design, Development and Verification/AIT Plan (DDVP), Configuration Management Plan (CMP), Component Control Plan, Deliverable Items List (includes product hardware and software deliverables), Deliverable Document List (includes contract regulated reports, plans, data packages, analyses, models, lists of components, parts, processes and materials, engineering documents, schedules, specifications, manuals, drawings, diagrams, ICDs, ConOps documents, processes and procedures), and Customer Furnished Item List.

This is due to several competing factors which we attempt to balance in this document:

- Australia has not undertaken a civilian government satellite development mission in several decades and as such does not have any current satellite development standards ;
- Australia recognises the benefits of Space 2.0 concepts and is not ready to fully accept all aspects of an existing standard like NASA or ESA; and
- The Satellite Cross-Calibration Radiometer mission and an Australian civilian government satellite development function is conceptual, pre-decisional and unfunded.

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[6] NASA (2016), Expanded Guidance for NASA Systems Engineering, Volume 1: Systems Engineering Practices, NASA/SP-2016-6105-SUPPL, Washington D.C., USA

7 Acknowledgements

This study was undertaken by the following study participants:

A full list of study participants can be found in Appendix A (Section 14).

8 Background

Satellite Earth observations contribute over $5 billion to Australia's annual GDP[7] through applications in industries as diverse as weather prediction, agricultural production, climate monitoring, climate adaptation, mining and extractive technologies, financial services, infrastructure development, environmental monitoring, and disaster management. Government agencies who depend on such services include Geoscience Australia, CSIRO, Bureau of Meteorology, and various Defence agencies. The US' Landsat satellite mission series and the European Sentinel satellite mission series have been, and continue to be, Australia's most important sources of Earth observations for land applications like agriculture, disaster mapping and environmental monitoring.

In 2019, a report commissioned by the Australian Government[8] found that combined Earth and marine observing is currently worth $29 billion to Australia, and $543 billion to Asia-Pacific Economic Cooperation (APEC) economies each year. The value to Australia is forecast to increase to $66.5 billion USD (approx. $A96 billion) by 2030. Having no Earth observing satellites of its own, Australia relies on partnerships with international satellite operators and space agencies to meet its Earth observation needs. Partners such as the United States Geological Survey (USGS), National Aeronautics and Space Administration (NASA) and European Commission (EC) operate satellites providing essential data to sectors representing approximately 75% of global GDP[9].

These global partnerships are built on a foundation of bi- and multi-lateral agreements, and a long-standing practice of collaboration in key areas such as data standards and processing, curation and distribution, and calibration and validation. Each component forms a crucial link in the supply chain that enables Australia to realise the full economic and scientific value of satellite data; calibration and validation are particularly vital as they ensure Australian governments and industry derive information from satellite data that is accurate and dependable.

In response to an approach in early 2019 from USGS and NASA to Geoscience Australia, as to whether Australia could potentially make a technological contribution to the US' Sustainable Land Imaging program (which includes the Landsat satellite missions), GA contracted UNSW Canberra Space to develop a report on the viability of domestic (Australian) contributions to international missions, specifically the US Sustainable Land Imaging program. The commissioning of this study follows long standing discussions between GA and the USGS around increasing our partnership with a space-based contribution[10], provided to the US by GA, concluding that Australia is positioned to contribute technology that stems from the global paradigm shift towards developing miniaturised dis-aggregated space systems with on-board processing. These types of technology are being actively developed and demonstrated by key players in Australia today – and can augment and add considerable value to the Landsat mission without contributing significant risk.

In 2019, USGS proposed the benefits of an SCR mission which both Australia and its US collaborators recognised as beneficial to the global remote sensing community given the proliferation of Earth observation missions. Without an improved means of inter-calibration, much of the benefit from these observations are difficult to extract. In late 2020, the US released a Requests for Information about potential contributions to the Landsat Next program. In addition to press releases from NASA/USGS contractors, the SCR series and the desire to launch the series to align with CLAREO-Pathfinder in late 2023 was established. Australia judged the Satellite Cross-Calibration Radiometer (SCR) series as the area in which the most valuable contribution to partner land imaging programs could be made. Accordingly, GA asked UNSW Canberra Space to perform, with

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[7] 2015. The Value of Earth Observations from Space to Australia. ACIL Allen Consulting Pty. Ltd.
[8] 2020. Current and future value of earth and marine observing to the Asia-Pacific region. Nous Group for the Australian Government.
[9] 2016. The Economic Impact of Geospatial Services. Alpha Beta Strategy & Economics.
[10] 2019. A possible Australian technical contribution to augment the US Sustainable Land Imaging program.

representatives from the Australian government Earth observations community, a technical / budget / schedule feasibility study for possible missions that would meet the requirements of such an SCR series, while being within the capability of the Australian space sector. A focus of the study was to examine how participation in a future SCR mission would contribute to the growth of the Australian space industry, advanced manufacturing capabilities, and the future up-skilling of the Australian space sector workforce.

The context for this study is the UNSW Canberra Space is the Australian National Concurrent Design Facility (ANCDF), which was established by UNSW Canberra with financial assistance from the ACT government and technical assistance from the French Space Agency (CNES). It is a concurrent engineering design facility in which rapid, accurate, immersive design and feasibility studies can be performed, with the space engineers and the customer/user sitting together for the purpose, to develop and test the viability of proposed missions to meet customer needs.

In recent years, studies in the facility have included: the NICSAT study, for and with, the National Intelligence Community: the AquaWatch study - for and with CSIRO; and the Lamanon intelligent-Earth-observing satellite study with CNES and Airbus. ANCDF is an above-the-line research-sector-operated national asset that complements the national spacecraft test facilities NSTF operated by the Australian National University.

9 Mission overview and background

This chapter provides a high-level overview of the mission, its scientific, policy and industry benefits and how it relates to other existing or planned international Earth observation satellite missions.

9.1 Mission concept

The high-level mission objective is as follows:

> The SCR mission programme would collect coincident spectral radiometer data between cooperative optical satellite missions for the purpose of enabling cross-calibration as a continuous, worldwide service.

Each of the SCR satellites in the programme would most likely be small satellites (<100kg) operating a hyperspectral sensor in a low Earth orbit (LEO). The orbit would be selected to enable coincident observation with both highly-calibrated optical missions (e.g. Landsat 8, Sentinel 2) and targeted cooperative missions (e.g. Planet Doves). It would thus be possible to transfer the radiometric response of the highly-calibrated reference mission to the target instrument. Consequently, the interoperability between the two observing systems is improved.

The mission architecture is depicted schematically in Figure 2. The system of interest consists of the SCR spacecraft, a network of ground stations and station-specific archives, a stitcher combining data from different ground stations into the mission archive and a L0 processor. As such, there are three main interfaces to related elements: Higher level data products are created by Geoscience Australia from the L0 data. The reference missions determine orbit and station keeping needs for the SCR mission, and its payload is tasked based on opportunities for coincident observations with the target missions.

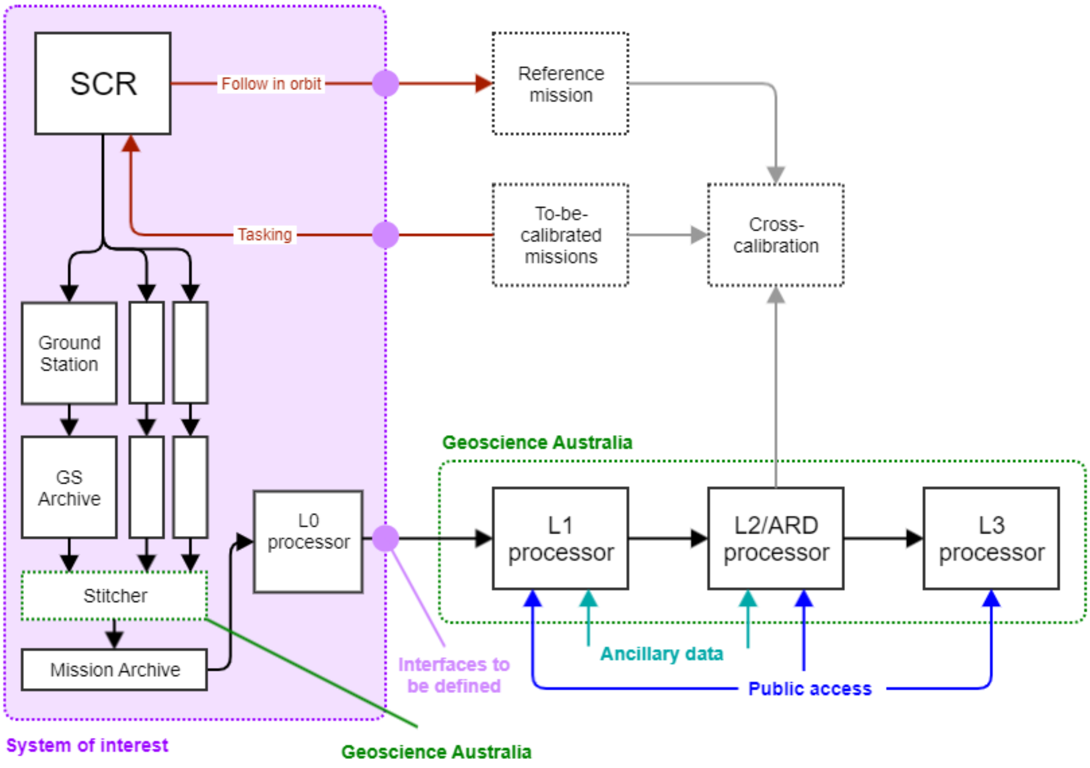

Figure 2 SCR mission architecture overview

9.2 Optical satellite cross-calibration

Traditional Earth observation missions such as MODIS, Landsat, Sentinel-2 and Himawari, operated by national institutions such as NASA, USGS, ESA and JMA, make use of on-board calibration to map, monitor and update calibration information as needed.

Radiometric calibration is a prerequisite for the creation of precise science data and higher-level image products. Calibrations are performed periodically and during the pre and post launch phases of the mission. The pre-launch calibrations are performed in well controlled laboratory conditions and are generally very rigorous. After launch, the instrument is allowed to stabilise and then another rigorous set of calibrations are performed. If the instrument meets the mission criteria, then the instrument will begin the Earth observation mission.

Vicarious calibration

On-orbit sensor calibration can be achieved using systems that are internal to the spacecraft. These include spectral lamp-based systems, as well as relay subsystems to project uniform solar or lunar flux across the sensor focal plane. These systems can provide full-aperture illumination of the optical imaging system or only through part of it. These techniques are well understood with subsystems deployed in numerous spacecraft. However, there are issues of reliability, design complexity as well as demands on the operation of the spacecraft for any or all these approaches.

Vicarious reflectance calibration is a method used to perform post-launch absolute radiometric calibration of EO sensors that is external to the spacecraft and makes use of natural or artificial sites on the surface of the Earth. These sites are quasi-stable in terms of surface spectral reflectance (for given angles of observation and illumination) because the surface topographical features change very little over time and spatially within the site boundaries. These areas are called pseudo-invariant calibration sites (PICS).

In practice this approach involves deploying personnel equipped spectro-radiometers and sun photometers and other instrumentation to measure the site surface reflectance and atmospheric properties. The measured data from the ground-based instruments are used in radiative transfer models to estimate the top-of-atmosphere (TOA) target radiances at the time of satellite overpass. These TOA radiances are compared with the satellite sensor readings to radiometrically calibrate the sensor. The uncertainty in the predicted or ground-truth TOA reflectance values is on the order of 2-3%.

These traditional calibration campaigns can be costly and time consuming. To reduce costs and increase the frequency of available ground-truth data automated sites have been stood up as part of the RadCalNet Radiometric Calibration Network[11] which currently consists of four sites in Namibia, France, China, and the U.S.A with a second site approved for China and a pending application for a site in Western Australia.

These sites could be used to transfer calibration between missions such as TRUTHS [12] or CLAREO-Pathfinder with an SCR layer and Earth observation missions such as Landsat and Sentinel-2 as well as providing a calibration for non-instrumented missions such as the Planet[13] constellation of satellites. Although the uncertainty in the predicted TOA reflectance associated with the automated sites is decreasing a dedicated vicarious calibration campaign would likely be required.

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[11] Bouvet et al., (2019), '*RadCalNet: A radiometric Calibration Network for Earth Observing Imagers Operating in the Visible to Shortwave Infrared Spectral Range*', Remote Sensing, Vol. 11

[12] Fox, N., and Green, P., (2020), *'Traceable Radiometry Underpinning Terrestrial-and Helio-Studies (TRUTHS): An Element of a Space-Based Climate and Calibration Observatory'*, Remote Sensing, Vol. 12

[13] https://www.planet.com/

Interoperability

A spaced-based calibration system would also improve efforts to make data from different instruments such as the Landsat Operational Land Imager (OLI)[14] and the Sentinel-2A Multispectral Instrument (MSI)[15] interoperable.

Interoperability refers to the ability to use the data from different instrument interchangeably or together in the same analysis. This process of cross-calibration verifies the absolute radiometric calibration accuracy of different sensors with respect to each other[16]. To accurately compare the sensor measurements the effects due to different spectral responses and spatial resolution must be taken into consideration.[17]. An equivalent reflectance can be obtained by spatially and spectrally matching pixels between the sensors. To do this spatially, the data from the sensors can be projected to the same mapping reference system and the higher resolution sensor, in this case MSI, can have the 10 m pixels averaged together to create 30 m pixels to match OLI. Spectrally matching pixels is more complicated to achieve as these multispectral instruments sample in discrete bands with different bandwidths and different responses across the bandwidths. Figure 3 shows the spectral response functions (SRF) for band 1 or the coastal aerosol band from OLI compared to band 1 from MSI.

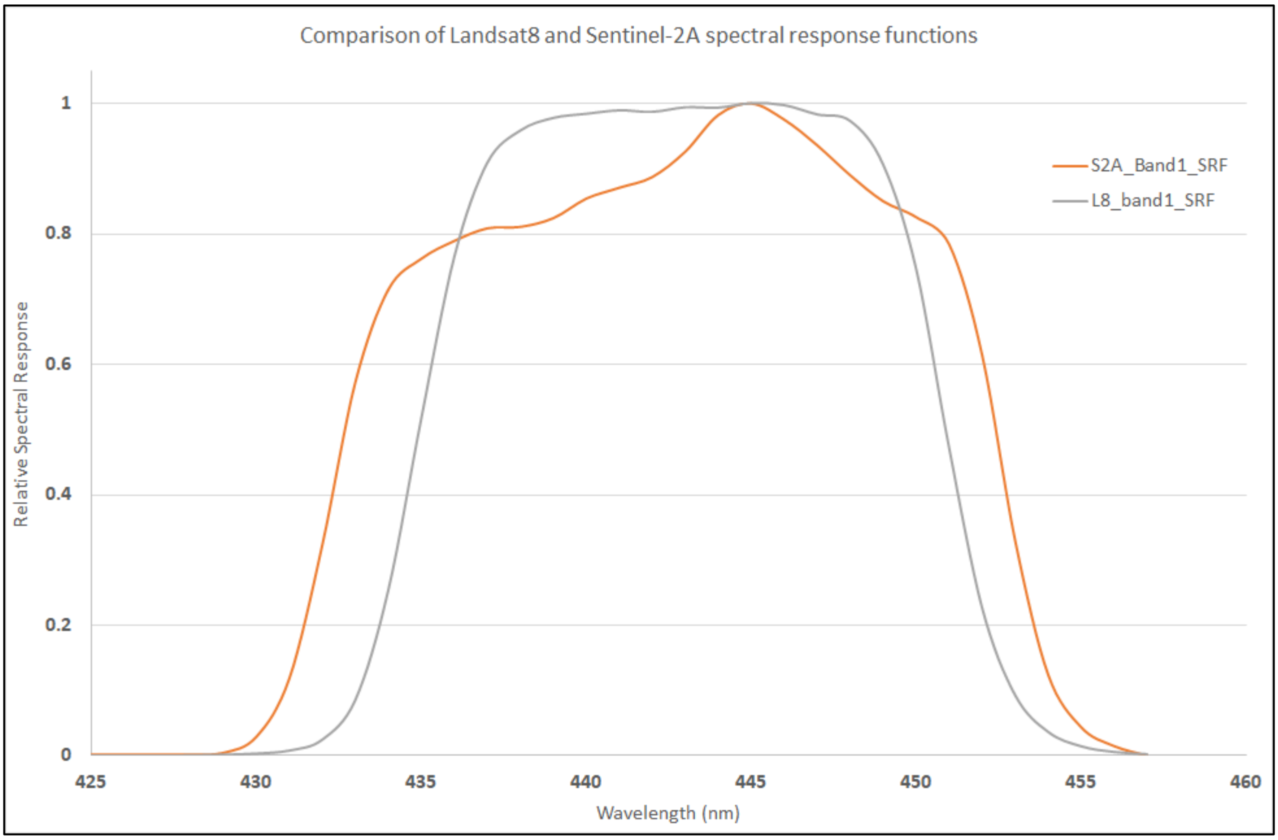

Figure 3 Comparison of Landsat8 OLI and Sentinel 2-A MSI SRF

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[14] https://www.usgs.gov/core-science-systems/nli/landsat/landsat-8?qt-science_support_page_related_con=0#qt-science_support_page_related_con

[15] https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/msi-instrumen

[16] Chander, G., et al., “Cross-calibration of the Terra MODIS, Landsat 7 ETM+ and EO-1 ALI sensors using near-simultaneous surface observation over the Railroad Valley Playa, Nevada, test site”, Proc. SPIE 6677, Earth Observing Systems XII, 66770Y (5 October 2007); https://doi.org/10.1117/12.734292

[17] Mandanici, E., and Bitelli, G., (2016), ‘Preliminary Comparison of Sentinel-2 and Landsat 8 Imagery for a Combined Use’, Remote Sensing, Vol. 8

If both sensors image the same target under the same conditions the reflectance will not be the same as the instruments do not exactly measure the electromagnetic spectrum in the same way.

If a third hyperspectral sensor also measures the same target under the same conditions, then there is a way to calculate a conversion factor between the two sensors. Hyperspectral data can be considered to by contiguous when compared to multi band instruments as they record data across the spectrum rather that in discrete bands. If the relative spectra response of a multi-band sensor is known, then a hyperspectral sensor can produce an equivalent reflectance by convolving the multi-band spectral response function with the hyperspectral reflectance signal. If two multi-band sensors and a hyperspectral sensor view the same target under the same conditions, then it is possible to calculate a conversion ratio (using the derived hyperspectral bands) which can be applied to one of the multi-band sensors to produce an equivalent reflectance between the two sensors.

This can be done by clipping or trimming the hyperspectral signal to the envelope created by the overlapping region from the MSI and OLI (or any sensor pair one wishes to compare) bands[18]. This is demonstrated in Figure 4.

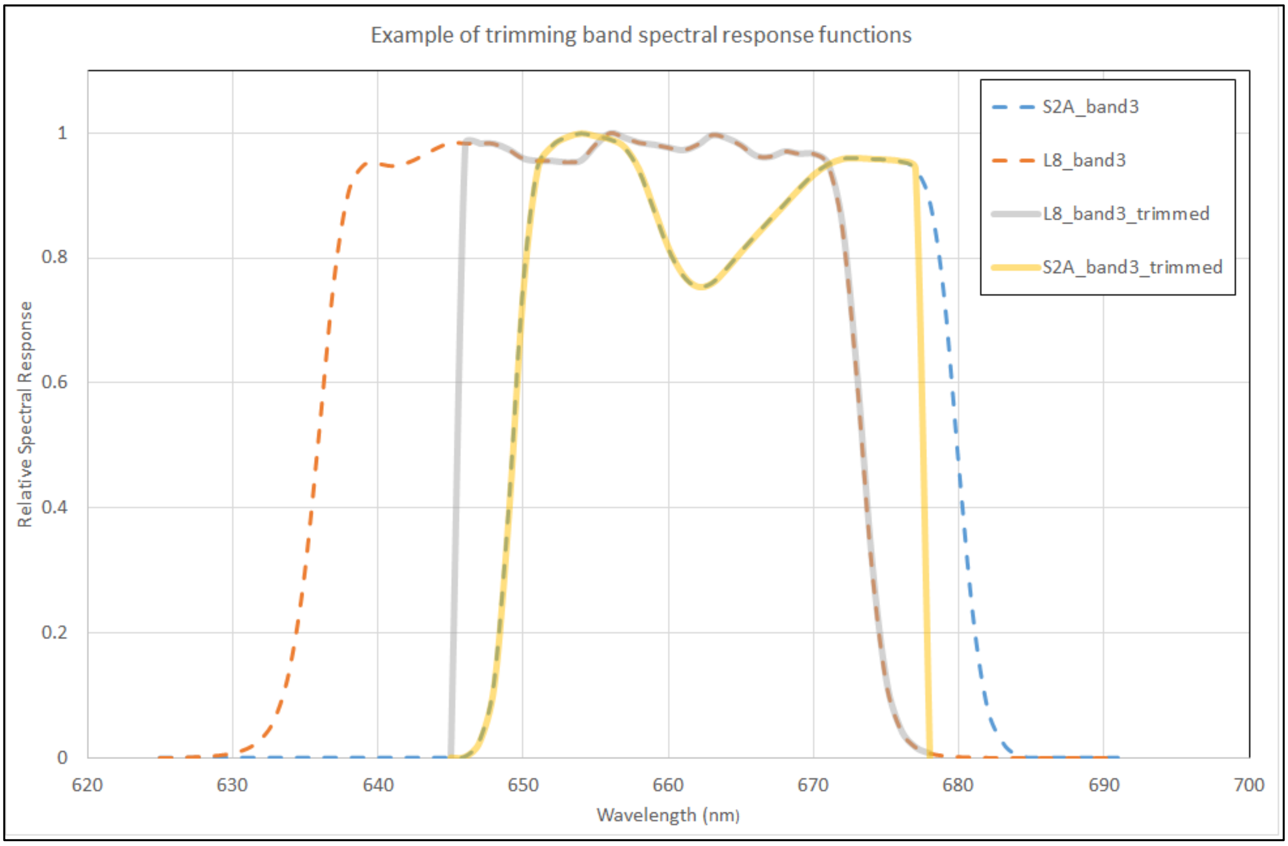

Figure 4 SRF band trimming example

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[18] Helder et al., (2018), 'Observations and Recommendations for the Calibration of Landsat 8 OLI and Sentinel 2 MSI for Improved Data Interoperability', Remote Sensing, Technical note, Vol.10

Such a conversion ratio or spectral band adjustment factor (SBAF) would allow the reflectance from one sensor to be more closely matched to another sensor as the difference in spectral response and bandwidth is removed from the comparison[19].

9.2.1 Steps to compare SCR to a designated reference sensor

1. SCR images Earth's CEOS calibration sites and imagery processed to Level-1t
2. Reference satellite (highly-calibrated, L8, L9, S2A, S2B, CLARREO, TRUTHS, etc) images CEOS calibration sites routinely and imagery processed to Level-1t
3. SCR mission tools identify near-coincident collections; land areas imaged by both satellites within ± 20 minutes (nominally) of each other.
4. User selects matching near-coincident imagery from both satellites for cross calibration, avoiding clouds and other problematic content.
5. SCR Mission Tools combines SCR hyperspectral bands into synthesized reference satellite data based on reference satellite relative spectral responses (RSRs).
6. Comparison is made of synthesized SCR data to reference satellite measured data on a per-band basis and differences in gain and bias determined.
7. This process is repeated often and with multiple reference satellites (i.e. not just one reference satellite to prevent biases).
8. Resulting differences with various reference satellites are examined by SCR Calibration Team and are used to re-calibrate SCR responses. (Note: This process must continue regularly throughout system lifetimes)

9.2.2 Steps to calibrate other satellites using SCR

1. SCR images Earth's CEOS calibration sites routinely and imagery processed to Level-1t
2. Target satellite (civil or commercial satellite) images Earth's CEOS calibration sites routinely and imagery processed to Level-1t
3. SCR mission tools identify near-coincident collections (land areas imaged with SCR nominally within ± 20 minutes of each other)
4. User selects matching near-coincident imagery from both satellites to uses for cross calibration, avoiding clouds and other problematic content.
5. SCR Mission Tools combines SCR hyperspectral bands into synthesized target satellite data based on target satellite relative spectral responses (RSRs).
6. Comparison is made of synthesized SCR data to target satellite data on a per-band basis and differences in gain and bias determined.
7. Note: Ideally, this process is repeated over different ground types represented in the CEOS calibration site list to identify stability of target system.
8. Resulting differences are used by the target satellite calibration team to calibrate the designated sensor system and processing (Note: This process must continue regularly throughout system lifetimes)

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[19] Chander, G., et al., "Use of EO-1 Hyperion data to calculate spectral band adjustment factors (SBAF) between the L7 ETM+ and Terra MODIS sensors," 2010 IEEE International Geoscience and Remote Sensing Symposium, 2010, pp. 1667-1670, doi: 10.1109/IGARSS.2010.5652746.

9.3 Benefits

The SCR mission would provide both scientific, policy and industry benefits. They are outlined in the following sections.

9.3.1 Scientific benefits

The US Academy of Science 2018 Decadal Survey for Earth Science (as well as the 2007 Decadal Survey) recommended the development of a space-borne radiometer to acquire high-accuracy spectral/spatial imagery of the Earth's surface and to provide highly-stable reference calibrations for other Earth observation sensors.

In fact, the Survey listed the establishment of reference radiance inter-calibration as one of its most important targeted observables. Such a reference radiometer would aid in enhancing the inter-operability of historic and future sensor datasets (e.g. Landsat) and provide improvements in the accuracy and reliability of climate science models.

In general, by moving the radiometric accuracy of optical analysis-ready data from a radiometric accuracy of 5% to 2-3% and a calibration that is stable to a fraction of a percent for month(s) at a time, it would be possible to improve the quality of optical Earth observation data to better support applications such as climate change modelling and ecosystem monitoring. Policy benefits

A core benefit of the SCR mission would be to secure Australia's data supply[20] because it will support the development of multi-mission space applications that provide EO data users with a degree of protection against international policy changes or technical failures. In addition, the programme would also provide a means to strengthen Australia's relationship with the US and other partners, helping bolster the case for ongoing access to their data.

SCR would provide a coherent end to the narrative of Australia relying entirely on international satellite data in a way that is consistent with the Australian narrative with the Committee on Earth Observation Satellites (CEOS) and Group on Earth Observations (GEO) of improving utilisation of global EO data, partnering, and making a unique contribution.

The continuous launch nature of this mission would support the scaling of capabilities including manufacturing in the Australian space sector. It thus extends Australia's sovereign capabilities from space utilisation into space hardware. In doing so, it would build Australian space heritage and increase the Technology Readiness Levels (TRL) of the Australian space sector. The result would be an increase of skills in Australia across the supply chain and within all related sectors.

The SCR mission programme would also create potential opportunities to formally partner on mission development with established space agency partners. This, in turn, provides a pathway for local stakeholders to access mentorship and support that helps develop their capability and bolster international profile.

9.3.2 Industry benefits

Accuracy and dependability are critical to ensuring satellite data is trusted by Australian government and industry. The 2020 report, *Harvesting the Benefits of Earth Observation*[21] (FrontierSI for the Australian Government) found a lack of trust in satellite data was a key factor in its relatively low adoption rates in the Australian agricultural sector. Addressing trust issues will help close the gap between potential and actual use of Earth observation in this sector which operates over more than half of Australia's landmass and contributes ~2.2% of our GDP.

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[20] University of Queensland, *Australia's access to Earth observation satellites is high risk*, https://www.spatialsource.com.au/remote-sensing/earth-observation-satellites-risk, accessed on 01/03/2021

[21] Frontier SI, *Harvesting the Benefits of Earth Observation*, https://www.frontiersi.com.au/wp-content/uploads/2020/08/FrontierSI_DigitalEarth_BenefitsEarthObservation.pdf accessed on 09/02/2021

Data accuracy is also a major concern in the rapidly developing commercial smallsat sector. Internationally, there has been an explosion in the number of satellites launched and slated for launch over the coming years – driven entirely by the smallsat (500kg or less) and mega-constellations of the Space 2.0 movement. These small, low-cost platforms tend to lack on board calibration, and therefore space-based calibration transfer or vicarious calibration using ground sites are critical.

9.4 Timeline

The development of the implementation timeline is based on a desire for SCR to operate in parallel with the CLARREO-Pathfinder mission (outlined below at section 9.6.2), expected to be launched in Q4 2023 with an operational life of 1 year.

In addition, the earliest possible operation of the SCR mission would enable coincident observations between instruments on the current series of Landsat satellites (Landsat 8 and soon Landsat 9) and a previous generation of the Landsat series (Landsat 7 and earlier). Landsat 7, the last of the previous generation of Landsat satellites is already operating well beyond its originally planned End of Life.

To achieve this desired timeline, an 18 month build and a 3-month commissioning schedule dictate that a decision to proceed would be required in late 2021.

Critical elements identified during the mission risk assessment (see section 11.1.7) as driving the schedule include:

- Establishing suitable arrangements for full flow of technical and other information between an Australian team and any foreign space agency teams working on similar concepts
- A few key technology de-risking activities (see section 11.6.4)
- A preliminary design activity of the space and ground segments of the mission (Phase B study)
- The time required for tender and procurement of the SCR missions once the previous activities are completed.

The proposed overall schedule is included in the schematic mission implementation plan that was shown in Figure 1.

To achieve the competing goals of achieving this challenging timeline and increasing the Australian industry content in the mission, a two-way pathfinder mission concept is proposed. A low-risk pathfinder mission would utilise COTS elements as far as possible to ensure a launch within the required timeline, while an Australian industry-focussed mission would be developed in parallel with a stronger emphasis on the Australian components rather than on meeting the Q4 2023 launch date.

The ensuing SCR missions would be launched in pairs every two years, i.e. SCR 3 and SCR 4 in 2025, SCR 5 and SCR 6 in 2027 and so on.

9.5 Orbit

The SCR spacecraft would be launched into low Earth orbits (LEO). There are two generic options for how the mission orbits can be defined depending on the selected operational concept:

1. **An optimised orbit maximising coincident observation opportunities with a selected group of reference and target missions**. This strategy would provide complete flexibility of defining the orbital parameters to enable coincident observations with as many of the target and reference missions as possible. Identifying such an orbit is a moderately complex task and is proposed as a precursor activity to any further mission design steps. In this scenario, the SCR mission would enable cross calibration between an arbitrary combination of other missions.
2. **An orbit of same altitude, inclination and RAAN as one reference mission and phased to trail that mission within a predefined time window**. Under this strategy the orbit is defined by the reference mission that is being followed and no detailed analysis is required. For the Landsat 8 and Sentinel 2 satellites the orbits would be sun-synchronous in altitudes of about 705km and 800km, respectively. In this scenario, the cross-calibration would be mainly limited to the reference spacecraft and any other missions that happen to achieve coincident observations.

The proposed study into the selection of a suitable orbit should also compare the above two generic options in terms of potential of their operational and scientific value.

These strategies would require that SCR has a station keeping capability in the form of an on-board propulsion subsystem to maintain the satellite within the required relative position to the reference satellite. Propulsion requirements in a pathfinder scenario are less demanding. Under certain conditions a no-propulsion option may even be conceivable for the first scenario but this would depend on the agreed mission objectives.

Further details on orbit selection and propulsion options that were carried out as part of this CDF study are provided in section 11.2.5 which recommends the following orbit candidates:

Table 2 Recommended Candidate Triple Coincidence Results (SCR, Landsat 8 and Sentinel -2A) (Repeated table)

Object ID	**Altitude (km)**	C_{To} **(days)**	**Overall**			**Over Land**		
			Total WRS2 Bins	**Unique WRS2 Bin**	**Average Overlap (km)**	**Total WRS2 Bins**	**Unique WRS2 Bin**	**Average Overlap (km)**
10019	645.98	48	60625	15277/28426	53.23	17382	5001/6954	53.29
10028	611.11	56	62106	16159/28426	51.83	17553	5408/6954	52.63
10030	649.96	60	60415	15457/28426	53.68	17583	5131/6954	53.63

9.6 Related missions

This section provides an overview of current and planned missions related to the SCR programme.

9.6.1 Landsat Next

Landsat 7 and 8 are currently operational and provide Earth observation image products for use by Australia for disaster response, land use monitoring, agriculture, resource exploration, and water security[22]. Landsat 9 is identical to Landsat 8, and is scheduled for launch in September 2021 to replace Landsat 7, which is nearing the end of its life[23]. Landsat 10 will provide an increase in the spectral bands provided by Landsat 8 and 9, including the Sentinel 2 bands, and additional bands for a total of 20 visible and near-infrared (VNIR)/short-wave infrared (SWIR) bands and 5 thermal infrared (TIR) bands[24]. The Landsat Next programme is expected to have multiple components, including a traditional imaging satellite or constellation, and companion satellites for calibration and experimentation[25,26].

9.6.2 NASA's CLARREO Pathfinder

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder Project is a NASA mission to launch a reflected solar spectrometer that will measure reflected solar radiation from Earth with an accuracy 5-10 times better than existing space-based sensors. This high accuracy allows changes in the Earth's climate to be detected much earlier than current sensors permit, which will help us understand how quickly the climate is changing and allow policymakers to respond more effectively[27].

CLARREO Pathfinder began development in 2016 and is expected to operate from the International Space Station (ISS) from Q4 2023. The spectrometer will also be used to demonstrate calibration of sensors on other Earth-observation satellites that cross paths with CLARREO Pathfinder[28]. However, the orbital dynamics of the ISS limit the number of Earth observing satellites and global regions that this calibration can service.

9.6.3 UK NPL's TRUTHS

The TRUTHS mission is a climate and calibration observing system designed to improve confidence in climate-change forecasts. TRUTHS stands for Traceable Radiometry Underpinning Terrestrial- and Helio- Studies, and will carry a hyperspectral imager to measure incoming solar radiation and outgoing reflected radiation with high accuracy achieved through an on-board calibration system conceived by the UK's National Physical Laboratory (NPL). This mission is expected to enable a 10-fold improvement in accuracy of Earth Observation data, halving the time required for climate scientists to determine changes in the Earth's temperature with high confidence[29]. The data from TRUTHS will also be used to cross-calibrate the sensors of other satellites[30], in a similar manner to NASA's CLARREO Pathfinder. The separate missions are complementary, with the two missions

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[22] Geoscience Australia, 40 Years of Landsat in Australia, http://www.ga.gov.au/news-events/features/40-years-of-landsat-in-australia, accessed 27 Jan 2021.

[23] USGS, Landsat 9, https://www.usgs.gov/core-science-systems/nli/landsat/landsat-9?qt-science_support_page_related_con=0#qt-science_support_page_related_con, accessed 27 Jan 2021.

[24] Newman, T., 2020, USGS Update on Landsat Next, https://www.fgdc.gov/ngac/meetings/december-2020/usgs-landsat-program-update-ngac-dec-2020.pdf.

[25] Christopherson, J., 2019, An SLI Cross-Calibration Radiometer (SCR) Concept for Improved Calibration of Disaggregated Earth Observing Satellites Systems, https://calval.cr.usgs.gov/apps/sites/default/files/jacie/Christopherson-Need-for-an-On-Orbit-Gold-Standard.pdf.

[26] Ball Aerospace, 2020, Ball Aerospace Selected by NASA for Three Studies to Develop Future Sustainable Land Imaging Technologies, https://www.ball.com/aerospace/newsroom/detail?newsid=124038.

[27] NASA, CLARREO Pathfinder, https://clarreo-pathfinder.larc.nasa.gov/, accessed 27 Jan 2021.

[28] NASA, 2016, CLARREO Pathfinder Undergoes Successful Mission Concept Review, https://www.nasa.gov/feature/langley/clarreo-pathfinder-undergoes-successful-mission-concept-review.

[29] ESA, 2019, THRUTHS: A New Potential ESA Earth Watch Mission, https://www.esa.int/Applications/Observing_the_Earth/TRUTHS_a_new_potential_ESA_Earth_Watch_mission.

[30] Airbus, 2020, Airbus Wins European Space Agency TRUTHS Mission Study for Metrological Traceability of Earth Observation Data, https://www.airbus.com/newsroom/press-releases/en/2020/11/airbus-wins-european-space-agency-truths-mission-study-for-metrological-traceability-of-earth-observation-data.html.

targeting sensors with different spatial resolutions and, TRUTHS measuring incoming solar radiation in addition to reflected radiation. Overlapping flights of the two missions, and any future missions, provide greater temporal coverage and opportunity to calibrate more sensors. Comparing data from the different missions also allows their uncertainties to be validated[31]. TRUTHS is being led by the UK Space Agency as part of the European Space Agency's (ESA's) Earth Watch programme[32]. The system feasibility and predevelopment phase of the mission is currently being undertaken by Airbus UK[33], with launch targeted for 2026[34].

9.6.4 CSIRO and SmartSat CRC's AquaWatch Australia

AquaWatch Australia is a program to monitor inland and coastal water quality from ground and from space - combining sensor data to create information products for the benefit of various downstream users. A second goal of the program is to grow Australia's space industry[35]. The programme is currently in phase 0, implemented by CSIRO and the SmartSat CRC together with a range of government and industry partners[36]. The main purpose of this phase is to identify user needs and identify technical and programmatic feasibility of the whole program. It is likely that AquaWatch, like SCR, will rely on a space-based hyperspectral instrument.

9.6.5 ANU's OzFuel mission

The ANU and Optus have joined to create a Bushfire Research Centre of Excellence pursuing various short, medium and long-term objectives to help detect bushfires and extinguish them shortly after ignition[37]. Part of this programme is a CubeSat mission named OzFuel. It will host infrared sensors to measure forest fuel load and vegetation moisture levels.[38] If deployed in a LEO constellation, OzFuel would enable near-real time analysis of fuel conditions supporting bushfires.

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[31] Fox, N. and Green, P., 2020, Traceable Radiometry Underpinning Terrestrial- and Helio-Studies (TRUTHS): An Element of a Space-Based Climate and Calibration Observatory, *Remote Sensing*, 12(15), 2400, https://doi.org/10.3390/rs12152400.

[32] NPL, Improving Earth Observation Data to Drive Improved Climate Change Modelling, https://www.npl.co.uk/earth-observation/truths, accessed 27 Jan 2021.

[33] Kuper, S., 2020, Airbus Wins ESA TRUTHS Mission Study for Metrological Traceability of Earth Observation Data, *Space Connect*, https://www.spaceconnectonline.com.au/operations/4612-airbus-wins-esa-truths-mission-study-for-metrological-traceability-of-earth-observation-data.

[34] Amos, J, 2020, Space Mission to Reveal 'Truths' About Climate Change, https://www.bbc.com/news/science-environment-51197453.

[35] SmartSat CRC, not dated, AquaWatch Australia, https://smartsatcrc.com/app/uploads/SmartSat_FactSheet_AquaWatch-FINAL.pdf, accessed 12/02/2021

[36] CSIRO, 2020, Space technology set to boost national water quality management, https://www.csiro.au/en/News/News-releases/2020/Space-technology-set-to-boost-national-water-quality-management, accessed, 12/02/2021

[37] ANU, 01/10/2020, ANU-Optus Bushfire Research Centre of Excellence, https://www.anu.edu.au/news/all-news/anu-optus-bushfire-research-centre-of-excellence accessed on 12/02/2021

[38] ANU, not dated, ANU-Optus Bushfire Research Centre of Excellence – Building a national defence system against catastrophic bushfires, https://www.anu.edu.au/files/resource/DVC200149%20ANU-Optus%20BRC%20brochure%20v6%20%28150ppi%29.pdf accessed on 12/02/2021

9.6.6 AusCalVal: Establishing Australia as a Global Leader in Delivering Quality Assured Satellite Earth Observation Data

Building on Australia's global reputation in satellite Earth observation calibration and validation, there are active discussions across Australia about a proposal to codify this position and developing AusCalVal. This strategy has four components:

1. a coordination body to oversee operations, communication, and access to data, facilities, and expertise – the Australian Centre for Earth observation Quality Assurance (ACE-QA);
2. a comprehensive, operational and research network of calibration and validation facilities across Australia;
3. a suite of tools and support provided via a unified service access point to enable national and international satellite operators to use the infrastructure and data collected for quality assurance; and,
4. an Australian owned and operated series of Satellite Cross-Calibration Radiometers to provide improved accuracy and consistency between optical satellites, e.g. domestic, international, and commercial operators.

This study is dedicated to item four of this strategy although the SCR mission will rely heavily on vicarious ground calibration delivered through items one, two and three to maintain mission performance.

9.7 Relationship between SCR and related missions

The CLARREO mission was recommended in the 2007 Decadal Survey to deliver needed climate model and sensor inter-calibration improvements. Although CLARREO was discontinued, the CLARREO Pathfinder (PF) mission began in 2016 to raise the TRL for the radiometer subsystems and to demonstrate the SI-traceable accuracies needed for improved intercalibration of multiple image sensors. CLARREO PF is slated for installation on the ISS in 2023. The HySICS spectrometer on CLARREO PF will use the sun and moon as calibration sources with a baseline objective of 0.3% (1 sigma) reflectance calibration uncertainty for the contiguous spectrum from 350nm to 2300nm, covering over 95% of the Earth's reflected solar spectrum.[39]

When CLARREO PF and TRUTHS are operational they will serve as a primary calibration layer with unparalleled determination of TOA spectral radiance. The SCRs would serve as a transfer layer and facilitate accurate and stable measurements of TOA radiance for cross-calibration of other EO imaging sensors

The SCR would provide another foundational system to achieve the higher accuracy and stable observations needed to reduce the radiometric uncertainties in optical sensor image data products. Specifically, the SCR would be a hyperspectral imaging spectrometer providing improved spatial resolution compared to CLARREO PF (from ~150 m to <100 m) and a radiometric uncertainty of 1% which can be transferred to other Earth observation platforms.

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[39] NASA, CLARREO Pathfinder, https://clarreo-pathfinder.larc.nasa.gov/, accessed 27 Jan 2021.

10 Mission elements

This chapter provides a high-level overview of all mission elements (see section 9.1) and compares differences in procurement stages to develop an estimate of ROM cost for each of them. This information is then used to establish a bottom-up ROM cost estimate for an SCR mission. The description of each element is kept brief here. Further details are provided in referenced sections within Section 10.

10.1 SCR summary

The main mission elements are listed in Table 3 together with an estimate of the rough order of magnitude (ROM) cost for the aspects of the SCR mission that would need to be procured. Note that the costs are listed for a single SCR mission with a COTS spectrometer such as those available from Headwall or other suppliers. At this stage, it is a valid assumption that this cost is valid for both the pathfinder missions as well as the first full operational SCR missions but not necessarily for the MMI integrated on a smallsat.

Initial non-recurrent developments needed for the pathfinder could be justified by the larger technical demands on the FOC missions in a first order approximation. For later missions, scale effects could be leveraged depending on the procurement details. Specific known uncertainties are covered by a local margin. For all other elements that show a margin of 0%, the uncertainty is covered through the 20% margin applied at the highest level.

The margins apply to the line in which they are listed. This means that the *Cost without any margin* column always lists each element's cost as derived if not considering any lower-level margins. The *ROM cost* column on the other hand applies the listed margin to the sum of the lower-level *ROM cost* (including the lower-level margin). For example, *SCR mission* ROM cost of AUD 36.0M is computed as the sum of the next lower-level ROM costs (0.4 + 4.0 + 4.1 + 1.6 + 20.0) = AUD 30.0M plus 20% margin.

Table 3 ROM cost estimate for a single SCR mission

Element	Cost without any margin	Margin (locally applied)	ROM cost
SCR Mission	**AUD 25.2 M**	**20%**	**AUD 36.0 M**
Ground Segment	AUD 0.4 M	0%	AUD 0.4 M
Launcher	AUD 3.6 M	10%	AUD 4.0 M
Mission Operations Centre	AUD 4.1 M	0%	AUD 4.1 M
Processing pipeline	AUD 1.6 M	0%	AUD 1.6 M
SCR Satellite	AUD 15.5 M	0%	AUD 20.0 M
Environmental Qualification	AUD 0.2 M	20%	AUD 0.2 M
Integration + System-level Tests	AUD 1.5 M	20%	AUD 1.8 M
Payload	AUD 1.8 M	30%	AUD 2.4 M
Payload Calibration	AUD 1.5 M	100%	AUD 3.0 M
Platform / Bus	AUD 10.5 M	0%	AUD 12.6 M

In parallel to the bottom-up cost estimation approach described above, the CoBRA parametric cost model[40] has been utilized to provide a sanity check of the mission cost. Details of the model are provided in section 11.6.5.

This approach yields a total mission cost of AUD 83M (FY2020) when adjusted for inflation and currency conversion with an error of ±25%. Due to the underlying cost data making up this model, its transferability to the modern Australian satellite manufacturing context is questionable.

In a calibration exercise, the model's cost estimate has been translated to the Australian context resulting in an adjusted cost of between AUD 17M to AUD 33M. This confirms the bottom-up figures derived here. Section 11.6.5.1 provides further details on the limitations and calibration of the CoBRA cost model.

Considering these findings leads to the conclusion that the estimated ROM mission cost provides a credible assessment of the actual SCR mission cost at this early stage of design. It is recommended a refinement of this cost assessment is performed as part of the next step in the mission development process, once the technical concept is properly refined.

The following sections provide for each of the mission elements listed in the bottom-up cost estimation:

- A concise description of what is included in each element
- A brief discussion on different procurement options (i.e. make vs. buy considerations). These are kept generic, ignoring any specific vendors or manufacturers
- An assessment of specific implementation options, listing potential vendors
- An estimate of the element's ROM cost and uncertainty if available

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[40] Yoshida, J. & Cowdin, M. & Mize, T. & Kellogg, R. & Bearden, D.. (2013). Complexity analysis of the cost effectiveness of PI-led NASA science missions. IEEE Aerospace Conference Proceedings. 1-14. 10.1109/AERO.2013.6496935.

10.1.1 Payload

10.1.1.1 Description

The SCR is envisioned to be a hyperspectral imaging spectrometer that provides the performance capability needed to meet the mission requirements which were refined in the study.

The SCR instrument would include a telescope and focal plane arrays to cover a spectral range from 400-2400 nm with a 10 nm band centre wavelength spacing. The instrument would provide SNR between 100 – 300 depending on the spectral band ranges. In addition, the SCR platform would include a means to accurately maintain radiometric calibration over the mission life. This could include a passive solar calibration unit or an on-board calibration subsystem.

10.1.1.2 Procurement approach aspects

Several options were considered for a SCR Pathfinder (PF) and SCR Full Operational Capacity mission (FOC). A review of the currently available instruments, and the descriptions of instruments being designed for use as the SCR, was conducted. The SCR mission requirement for radiometric accuracy places demanding instrument requirements on both the optical and detector subsystems.

An off the shelf instrument is currently unavailable and to fulfil the SCR FOC mission a bespoke hyperspectral imaging spectrometer would be required to meet all the SCR mission requirements.

10.1.1.3 Implementation options

Several options were considered for a SCR PF and SCR FOC mission. A review of the currently available off the shelf instruments and those being designed for use to support the Sustainable Land Imaging program was conducted. Details of these options are discussed in section 11.3.3. Potential manufacturers include Ball Aerospace, Cosine NL, Headwall Photonics, or an Australian entity.

10.1.1.4 Element cost estimate

Based on previous experience and expert opinion - in combination with confidential quotes for commercial instrument options, the cost for the payload, including development, build and space qualification testing is expected to be AUD 1.8M with a relatively large uncertainty of 30%.

10.1.2 Spacecraft bus

10.1.2.1 Description

The spacecraft bus houses all the necessary systems required to accommodate and support the payload for both the launch and in-orbit operational phases of the mission.

The spacecraft bus is a significant portion of the spacecraft and typically consists of the following components:

- Structure, including launch vehicle interface
- Electrical subsystem: batteries, solar arrays, and Electrical Power Supply (EPS)
- Communication subsystems: radios and antennae
- On-Board Computers (OBCs)
- Attitude Determination and Control Subsystem (ADCS): reaction control wheels, magnetorquers, magnetometers, Coarse Sun Sensors (CSS), Earth Horizon Sensors (EHS), GPS, and star trackers (sometimes integrated with optical payloads)
- Thermal control subsystem
- Propulsion subsystem: thruster, propellant storage devices/tanks, and power management system (for electrical propulsion systems)

For this mission, it was estimated that a microsat sized spacecraft – weighing approximately 30 to 50 kg and measuring approximately 50 x 50 x 50 cm (payload included) – would be most appropriate given the expected payload weight and dimensions.

10.1.2.2 Procurement approach aspects

To procure microsat buses, two options are available:

- Procure an off-the-shelf microsat bus from a satellite provider.
- Contract the development of a custom microsat bus from a satellite developer/integrator.

Note that all identified off-the-shelf microsat systems are from overseas suppliers (see section 11.6.3) and therefore these spacecraft, or components of these spacecraft, may be subject to export control.

10.1.2.3 Implementation options

For off-the-shelf microsat buses, the following options were identified as being suitable for the GA SCR mission and are available:

Table 4 Overview of suitable micro-satellite platforms

Supplier	Country	Microsat Bus	Comments
Ball Aerospace & Technology Group	USA	BCP-100	Datasheet[41]
Berlin Space Technology	Germany	LEOS-50	Datasheet[42]
Momentus	USA	Vigoride	Datasheet[43]
Raytheon (previously Blue Canyon Technologies Inc.)	USA	X-Sat	Datasheet[44]
RocketLab USA	USA	Photon	Datasheet[45] Includes launch[46]
Satellogic	Argentina		
SITAEL	AUS	S-50, S-75	Datasheet[47]
SSTL	UK	SSTL-Micro	Datasheet[48]
York Space Systems	USA	S-CLASS	Datasheet[49]

For contracting the development of a custom satellite bus with an Australian organisation, the followings have been identified as having the necessary skills and experience to grow and develop microsat spacecraft systems: Inovor, SkyKraft, UNSW Canberra Space, and potentially Sitael.

10.1.2.4 Element cost estimate

An Australian-made bus is expected to cost around AUD 10.5M as derived in detail in section 0. This number is reduced to between AUD 4.3M and AUD 7.2M when procuring a COTS bus from overseas vendors.

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[41] http://www.ball.com/aerospace/Aerospace/media/Aerospace/Downloads/D3072_BCP100-ds_1_14.pdf?ext=.pdf
[42] https://www.berlin-space-tech.com/wp-content/uploads/2020/07/PFR-PR28_LEOS-50__V1.00_.pdf
[43] https://momentus.docsend.com/view/xmuxgesufvqfqh8p
[44] https://www.bluecanyontech.com/spacecraft
[45] https://www.rocketlabusa.com/satellites/
[46] https://www.nasaspaceflight.com/2020/09/rocket-lab-debuts-photon/
[47] https://www.sitael.com/space/small-satellites/systems/
[48] https://www.sstl.co.uk/getmedia/78c3ae88-0f17-40a1-9448-8c3c7e9f6944/SSTL-MICRO.pdf
[49] https://www.yorkspacesystems.com/s-class/

10.1.3 Integration and system-level testing

10.1.3.1 Description

Integration and system-level testing begins after the individual subsystems and payloads are assembled and tested at a component level. Spacecraft integration activities involve the preparation, assembly, and initial integration tests of subsystems and payloads into the spacecraft structure (bus), along with the connection of electrical harnesses and heat straps to complete the final spacecraft.

All spacecraft integration procedures require a degree of contamination control, since spacecraft are sensitive to particulates, oils and greases, metal filings, and other foreign matter as the vacuum and weightlessness of space may cause these to coat optics, cause electrical shorts, and add to debris in orbit. This requires spacecraft to be integrated in special cleanrooms equipped with appropriate air filtration, electro-static discharge (ESD) flooring and workbenches, cleaning equipment such as ultrasonic cleaners, and necessary clothing to prevent people from directly contaminating the spacecraft. In addition to this, cleanrooms must be stocked with all necessary tools and equipment for assembling, handling, calibrating, and sometimes testing components of the spacecraft.

The system-level testing phase is where the integrated spacecraft with fully developed flight software is rigorously tested to ensure that the spacecraft functions as intended as a complete system. System-level testing is also where the operators get to know the spacecraft intimately and discover operational issues before it is too late to fix them. It is critical that this testing mimics on-orbit operations as closely as possible, which means using the operations software to command the integrated spacecraft over-the-air (no cables) with the spacecraft running the flight software that it would be launched with. This ‘test as you fly’ approach uncovers bugs and idiosyncrasies that cannot be identified in earlier component-level testing. It is best practice to heavily involve the spacecraft operations team in planning and execution of system level testing

10.1.3.2 Procurement approach aspects

Procurement of integration and system-level testing services would typically be performed by the spacecraft bus integrator, but a third party could be sourced.

10.1.3.3 Implementation options

For spacecraft integration, the system integrator would procure all required subsystems and payloads and run assembly, integration, and system-level test activities. Alternatively, the bus and payload could be contracted, with integration performed by either organisation or by a third party who then performs testing.

10.1.3.4 Element cost estimate

Spacecraft integration and system level testing are expected to cost approximately AUD 1.5M. When applying a margin of 20%, the estimated cost is AUD 1.8M. This cost assumes that four months are required for spacecraft integration in a cleanroom facility, with FTE staffing of two engineers. Six months in a cleanroom facility are required for system level testing, with FTE staffing of six engineer.

10.1.4 Payload calibration

10.1.4.1 Description

The purpose of calibrating EO sensors is to ensure the characteristics of a remote object are accurately and reliably estimated over time. EO sensors require calibration to quantify the sensor’s response to known radiometric input and to characterize the interactions and dependencies between the sensor optical, mechanical, and electronic components. Systematic biases are thereby identified through calibration.

The radiometric performance requirements for SCR are, by definition, extremely demanding and will require exceptionally reliable and accurate calibration of the instrument both on-ground and in flight.

10.1.4.2 Procurement approach aspects

Due to the high cost and technical complexity of instrument calibration it is not cost-effective to build such a facility in Australia. Ideally, a collaboration with international partners in this area would provide an additional opportunity to increase Australian expertise for future space missions.

10.1.4.3 Implementation options

The on-ground radiometric calibration of the SCR would take place in a facility which provides SI traceable sources and known radiance to better than 1% accuracy in terms of spectral value and uniformity. An example facility is the NASA Goddard Laser for Absolute Measurement of Radiance (GLAMR)[50].

An on-board radiometric calibration approach could consider at least an LED-based illumination subsystem that provides radiometrically accurate and spatially uniform illumination of the focal plane(s). A passive solar calibration subsystem based on a full or partial aperture diffuser might be deployed, as the sun is a well-known and stable source. However, this adds complexity to the instrument that may not be necessary. The SCR would also maintain calibration by imaging of selected pseudo invariant calibration sites (PICS) on the Earth (some of which are part of the instrumented RadCalNet network and provide a direct measurement of surface reflectance) and monthly imaging campaigns of the moon

In addition to radiometric calibration, the SCR detectors and the optical system would be aligned during AIT operations and assessed for image quality and calibrated to generate correction factors such that each pixel is in the desired position. In-flight geometric calibration would be performed by imaging designated terrestrial target areas as part of on-going calibration operations so that image quality, georeferencing and image-to-image registration capabilities can be monitored.

The calibration concept is further detailed in section 11.3.2.

10.1.4.4 Element cost estimate

Costing for this element assumes that a calibration facility is provided by an international partner and that only facility use, travel and personnel costs need to be paid for. The cost estimate for the payload calibration under these assumptions is AUD 1.5M with a very large uncertainty of 100%. This implies that a large fraction of this cost - namely the facility access fee - may be supplied in kind by an international partner.

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[50] https://glamr.gsfc.nasa.gov/

10.1.5 Environmental qualification and launch

10.1.5.1 Description

Environmental qualification testing forms part of an overarching effort to provide total mission assurance, i.e. establish the highest level of confidence possible that the fully integrated system (spacecraft bus + payload) would operate correctly in orbit, resulting in a successful mission. The environmental qualification test program is intended to demonstrate that the as-built system would perform correctly when subjected to a range of environmental conditions (launch + on-orbit operations) more severe than expected during the mission to verify positive design margins. The environmental stress screening activities further serve to identify any workmanship defects that could jeopardise the success of the mission. Formal system qualification tests are conducted on a flight representative engineering model (EM) spacecraft, and the flight model (FM) spacecraft would be exposed to reduced acceptance level test requirements for flight acceptance by the launch service provider (LSP).

Detailed environmental qualification requirements depend on the specific mission requirements, the LSP and launch vehicle (LV) selected to deliver the system to orbit. The LSP would stipulate the environmental qualification test requirements which need to be satisfied so that the space system can be accepted for launch into orbit. Therefore, it is critical to baseline a LSP and LV at the outset of the project and engage with the LSP throughout the entire test program to avoid undesired schedule delays and cost excursions later in the project. The latter further minimises the risk of over testing - reducing the risk of unnecessary hardware failure. The requirements, along with a detailed description of the test schedule shall be included in the system verification specification and plan developed at the outset of the project. Environmental qualification testing is typically conducted at a high level of integration on a system that is flight-representative (or as close to as possible). Any deviation from the flight-like configuration requires justification and approval from LSP. In addition, relevant qualification and verification activities may be conducted at several other stages and lower levels of integration along the AIT process to provide confidence in the system’s operation and compliance with the system requirements as outlined in section 11.1.1.

The relevant environmental qualification tests to be conducted are listed below:

1. Structural model shock test (test results used to correlate spacecraft structural model)
2. Structural test model vibration test (test results used to correlate spacecraft structural model)
3. Engineering model thermal cycling (atmospheric pressure environment)
4. Engineering Model qualification level shock test (**required by LSP**)
5. Engineering Model qualification level vibration test (**required by LSP**)
6. Engineering Model EMC test
7. Engineering Model thermal balance (Vacuum) testing (test results used to correlate spacecraft thermal model)
8. Flight Model Thermal Cycling (vacuum) and Vacuum bakeout (**required by LSP**)
9. Flight Model acceptance level vibration test (**required by LSP**)

10.1.5.2 Procurement approach aspects

Environmental qualification testing is a critical part of the project workflow and requires suitable facilities and appropriately trained personnel to ensure a successful environmental qualification test campaign. The National Space Test Facility (NSTF) at the Australian National University (ANU) at Mt Stromlo in Canberra can provide the full range of testing services required for environmental qualification of the SCR mission - except for shock testing. Shock testing can be performed by alternative test houses such as VIPAC in Melbourne and Austest in Sydney. The NSTF includes an anechoic chamber, optics integration laboratories, process laboratories for high precision cleaning, class 100 cleanroom with crane and optical tables, large thermal vacuum chamber, a vibration test facility, and mass properties measurement equipment for centre of mass (CoM) and moments of inertia (MoI, principal axes only). NSTF personnel have the relevant experience to perform spacecraft environmental qualification testing and have the necessary ESD and contamination control procedures in place. Other test houses may not be familiar with the particularly strict handling requirements of space system hardware. Significant additional costs may be incurred if additional equipment is required, and stricter process requirements are requested.

International travel to access overseas test facilities bears significant risk of hardware damage during transport and would incur additional personnel travel cost as well as increased administrative burden with regards to export/import control licenses.

10.1.5.3 Implementation options

The NSTF is the only facility of its kind in Australia. The co-location of all required integration and test facilities represents a significant advantage as it reduces risk, cost, and administrative burden of coordinating multiple stakeholders.

10.1.5.4 Element cost estimate

The cost for this element is estimated at AUD 200K with a 20% uncertainty margin. The details of this estimate are provided in section 11.6.1.

10.1.6 Processing pipeline and data distribution

The SCR data products would be defined according to international standards (as are all space based EO image data products), generated by an autonomous processing chain and distributed to the international user community. These data would be systematically corrected both radiometrically and geometrically as well as orthorectified and transformed from at-aperture sensor radiance to surface reflectance or temperature. Product quality assurance and control would also be part of the data processing chain.

The data products would likely be interoperable with other product providers - following for example, the CEOS (Committee on Earth Observation Satellite) Analysis Ready Data for Land (CARD4L) framework guidelines and processes[51]. CARD4L will enable users to obtain image data products for a host of land study applications that is ready to be used and analysed[52]. It is likely that SCR data products will also adhere to these definitions.

10.1.6.1 Description

The data processor pipeline consists of one data assembly phase ('stitching') plus four processing stages (L0, L1, L2, L3). The stitcher would be provided by GA and would interface the mission archive to the L1 processor. A further description can be found in section 11.5.4.

A focus on secure software development should be made to ensure the risk of any cyberattack is sufficiently mitigated. See section 10.1.8.1 for possible impacts and relevant documents.

10.1.6.2 Basic product definitions

The following SCR data products definitions were considered in the study and follow standard data process level terminology[53].

Level 0 (L0) product

- Raw observation data after restoration of the chronological data sequence for the instrument operating in observation mode, at full space/time resolution with all supplementary information to be used in subsequent processing (e.g. orbital data, health, time conversion, etc.) appended, after removal of all communication artefacts (e.g., synchronization frames, communications headers, duplicated data). Level 0 data are time-tagged. The precision and accuracy of the time-tag shall be such that the measurement data will be localized to accuracy compatible with the Users requirements. Also includes raw observation data after restoration of the chronological data sequence for the instrument operating in calibration mode.

Level 1 (L1) product

- Level 1a: Level 0 data with corresponding radiometric and spectral correction and calibration computed and appended, but not applied, and possibly with preliminary geometric correction not altering the radiometry.
- Level 1b: Level 1a data not re-sampled, quality-controlled, and radio-metrically calibrated, spectrally characterised, geometrically characterised, annotated with satellite position and pointing, geolocation inferred from satellite pointing information and preliminary pixel classification (e.g. land/water/cloud mask).

Level2 (L2) product

- Derived geophysical variables at the same resolution and location as Level 1 source data.

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[51] https://ceos.org/ard/index.html
[52] A. Lewis et al., "CEOS Analysis Ready Data for Land (CARD4L) Overview," IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium, 2018, pp. 7407-7410, doi: 10.1109/IGARSS.2018.8519255.
[53] https://earthdata.nasa.gov/collaborate/open-data-services-and-software/data-information-policy/data-levels

Higher level or value-added products provide biophysical and/or geophysical data and are generated by the Level 3 (and above) Processor. These products were not addressed in the study and are yet to be defined.

Typically, the ground segment allows for storage of all Level 0 products along with their relevant calibration data applied so that higher level products can be generated at any time. But this strategy, though valuable, puts strain on the data transmission, storage, and management infrastructure. Issues concerning data archiving and degradation were not addressed in the study. Clear mission objectives, applications and products should be defined as part of a Phase A/B follow on study as these products directly impact the required SNR for the spectrometer and ultimately the instrument design.

A notional workflow to generate a Level 0 and Level 1 product in the ground segment processing pipeline from the raw image data generated on-board the spacecraft is shown in Figure 5.

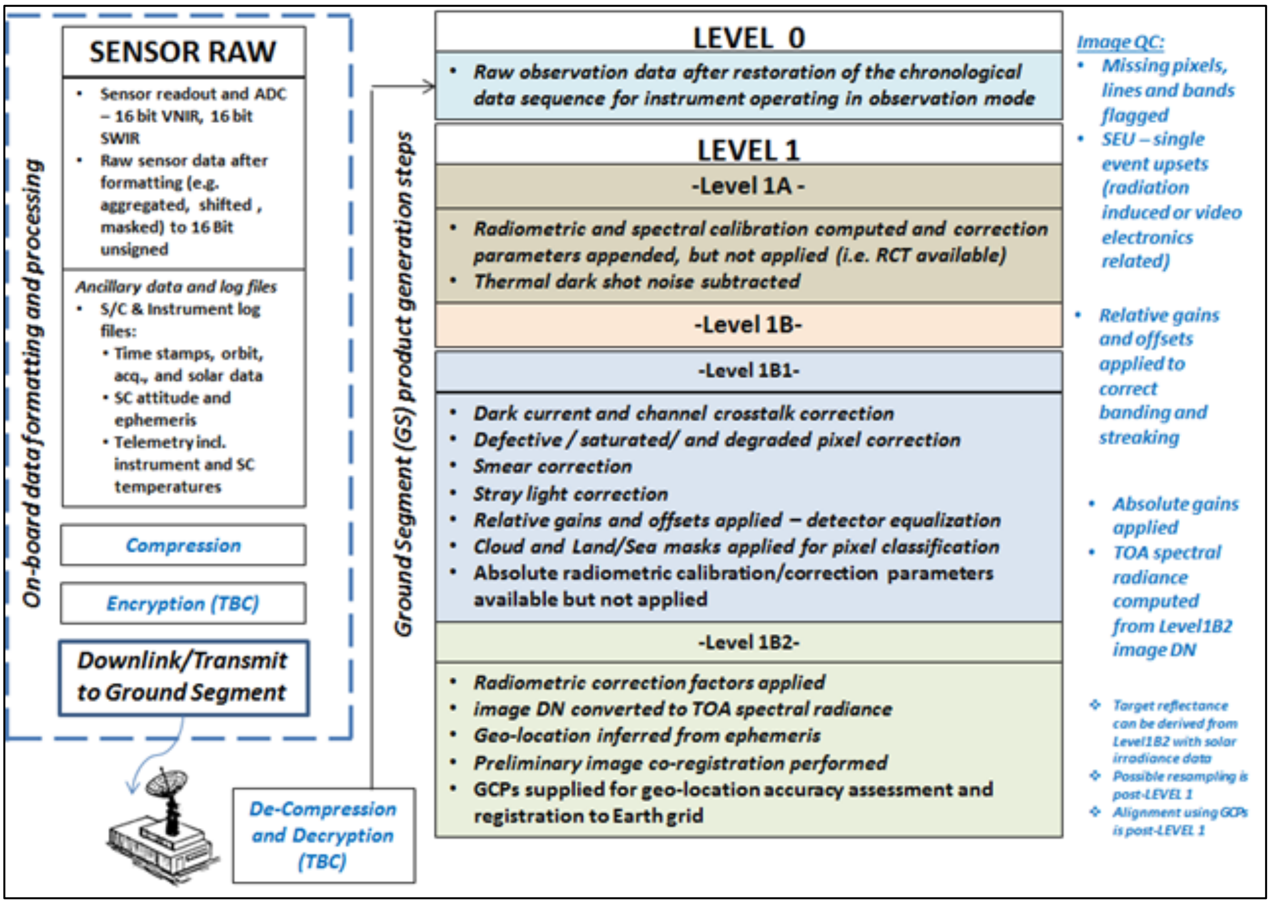

Figure 5 Product generation workflow (notional)

These product levels are explored further in Section 11.5.4.1.

10.1.6.3 Basic product formats

Digital image file formats vary depending on the sensor. Most formats are supported by most image processing software vendors so that files can be read with generic image processing and display tools. The Geographic Tagged Image-File Format (GeoTIFF) is a common format where cartographic and geodetic information association with the image is included in the file metadata.

The SCR standard data products would adhere to standards covering processing, formats, validation, and dissemination. Product offerings should be selectable by the user and could include options such as band sequential (BSQ), band interleaved by pixel (BIP) and band interleaved by line (BIL), JPEG2000, and GeoTIFF,. The files would include the proper ASCII header information for each file type and be readable by image processing tool suites that are currently in use (e.g. ENVI, ArcGIS).

The definitions for SCR image file formats would be included as part of the wider mission data management architecture.

10.1.6.4 Procurement approach aspects

The L0 processor could be developed internationally or locally. The development of the L0 processor is a relative unknown if the work is performed locally, with more experience located internationally. L0 processors have been developed internationally for other missions, so there is a body of knowledge and experience that can be drawn from.

Generally, L0 data processors are bespoke to the mission series and need to be developed to work with the unprocessed payload data received from the spacecraft. It is unlikely that an existing/COTS L0 data processor that meets the requirements of the mission (without further work) could be procured. The level of re-use is dependent on the data format similarity coming from the spacecraft. A general software consultancy/team would be suitable, however a group with space systems knowledge would be preferred.

10.1.6.5 Implementation options

The implementation should generally adhere to or follow best-practice EO community standards for the L1, L2, and L3 data processors. Relevant standards may include ISO 19131[54], ISO 19112[55], ISO 19115[56], COG[57], STAC[58], and the CARD4L initiative.

Data outputs from each stage should be appropriately licensed to maximise uptake (and thus national benefit) of the generated products. This may be achieved by licensing the data products under an ‘open’ license, such as CC BY[59] (or a variant thereof). Restrictive licensing may lower the acceptance and usage of the data products by organisations and consumers, or act as a barrier to their usage.

SCR data could also be integrated into NASA’s Earth Science Data and Information system (ESDIS)[60] which would place requirements and interface controls on the data product specifications, storage, and public distribution.

10.1.6.6 Element cost estimate

Only the development of the L0 processor was included as part of the mission definition and is expected to cost AUD 1.6M. This figure is conservative due to the higher risk identified in section 10.1.6.4. The cost of the higher-level processors was not considered within the context of the study.

10.1.6.7 Stitching Background

Processing pipelines (Products from the NASA Data Processing Levels) are well understood within the Earth observation community, but ground station stitching is not often undertaken for land imaging missions hence additional background is required.

Ground reception stations can only receive data when the spacecraft is in line of sight, and that is successful only if there are no equipment malfunctions, radio frequency interference, or conflicts with other higher priority spacecraft. A network of reception stations can overcome, or mitigate, these

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[54] https://www.iso.org/standard/71297.html
[55] https://www.iso.org/standard/70742.html
[56] https://www.iso.org/standard/53798.html
[57] https://www.cogeo.org/
[58] https://stacspec.org/
[59] https://creativecommons.org/licenses/by/4.0/
[60] https://earthdata.nasa.gov/collaborate/new-missions

limitations by extending the spatio-temporal coverage of reception and providing multiple pathways to receive the data. Stitching realises the opportunity afforded by a ground station network to deliver the back-end ground processing required to merge the data streams from the spacecraft.

The objective of stitching is to create the most complete and highest possible quality Level-0 data stream in the shortest possible time after spacecraft overpass. In addition, this process could be used to create near-real-time quick look images.

The Australian National Ground Station Technical Team operates a ground station stitching network for the AVHRR, MODIS and VIIRS sensors received by ground stations within their network. The software to perform the merging was developed at CSIRO in the late 1990s and has been in continuous operation ever since.

An example for the results of the stitcher is provided in Figure 6. The imagery is shown in satellite (swath) projection. The coast of Western Australia is visible in the right-hand side of each scene, north is towards the top. Note that the final stitched pass is both longer and does not contain the missing lines evident at the southern end of the Darwin and Alice Springs passes.

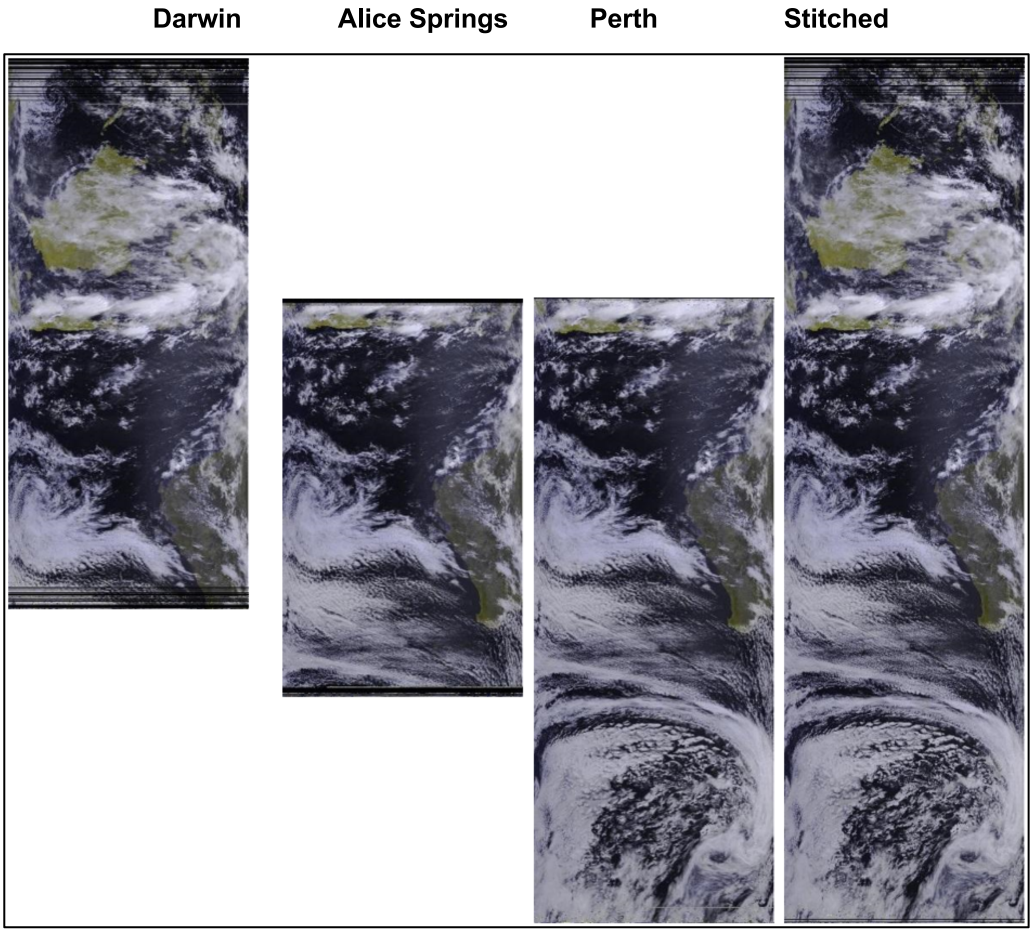

Figure 6 An example of the currently operational Australian pass stitching system using NOAA-17, data generated by the Australian National Ground Station Technical Team[61]

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[61] www.angstt.gov.au

10.1.7 Mission Operations Centre

10.1.7.1 Description

A Mission Operations Centre (MOC) is required for the satellite operators to control the SCR series spacecraft, monitor their health, respond to anomalies, and make payload data available to mission stakeholders. The level of staffing and infrastructure required for the MOC depends on the complexity of the spacecraft, the level of autonomy built into the spacecraft and operations software, the risk tolerance for the mission, and the data volume to be handled. For example, it is possible to reduce staffing levels if certain anomalies are handled autonomously by the spacecraft, and/or anomalies can be detected by the operations software and an on-call operator automatically notified. A 'lights out' approach is recommended, like Planet's approach[62], where a certain level of ground segment and space segment automation reduces the person-hours required for operations, and removes the need for a dedicated operations centre with 24/7 staffing.

With this approach in mind, the MOC can be, but does not need to be, a centralised workspace that the operations teamwork from. A modern MOC implementation features a secure web-based approach to operations, that allows the operators to work from distributed and secure operations facilities.

10.1.7.2 Procurement approach aspects

The MOC would be procured as a customised item from an Australian or international provider. As the MOC is always a customised element of a mission there are no COTS options available.

10.1.7.3 Implementation options

The infrastructure required for the MOC is primarily software. This software could be developed from the ground up, or an existing local or overseas system could be adapted to meet the needs of the SCR series spacecraft. Examples of existing systems in Australia are those developed by UNSW Canberra Space for operation of the Buccaneer Risk Mitigation Mission, M1, M2 Pathfinder, and M2 missions, or the mission control centre (RSOC) that is currently under development by Saber Astronautics for the Australian Space Agency.

For example, the RSOC in Adelaide offers advanced mission operation services including orbit overpass and prediction, spacecraft health degradation (AI diagnostics), signal's interference, space weather live tracking and prediction models, space traffic, pattern of life, threat & safety analysis, ground sensor network services and commanding / tasking and schedulers.

10.1.7.4 Element cost estimate

The MOC is estimated to cost AUD 4.1M, a breakdown of which is shown in Table 21 in section 11.2.2. The cost consists of the person time required for development, validation and verification, and ongoing support of the operations infrastructure described in section 10.1.7.1, as well as operator training, and mission operations planning and execution. The cost does not include operator involvement in system level testing, which is covered in section 11.2.2.

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[62] Henely, S., Baldwin-Pulcini, B., and Smith, K., 2019, Turning Off the Lights: Automating SkySat Mission Operations, *33rd Annual AIAA/USU Conference on Small Satellites*, Utah, USA.

10.1.8 Ground stations

10.1.8.1 Description

The mission would utilise S-band for TT&C (uplink/downlink) and X-band for science data transfer (downlink only).

The preliminary payload link budget (section 11.3.4) indicates that the ground station network would need to consist of Tier 1 stations, with Tier 3 stations inadequate due to their low antenna gain. A Tier 1 station would typically support link bandwidths in the range 100-1000Mbit/s, utilising a ~9 metre parabolic antenna to provide sufficient gain[63]. Approximately 75 contact minutes per mission per day are required to meet the data budget required for the mission. Tier 1 and Tier 3 S-band ground stations can be used for TT&C as the required data rates are lower, allowing the TT&C link budget to be satisfied with Tier 3 stations. Using Tier 3 stations for TT&C reduces contention for Tier 1 stations.

A ground station interface would be required to allow the ground stations to be tasked by mission operators. The interface would bridge individual ground stations' tracking interfaces to the scheduling and tasking software used in the mission operations centre. GA should manage and operate the tasking interface within their network to reduce the surface area of publicly exposed interfaces. Cybersecurity risks should be considered and managed appropriately. Possible risks include a data breach, network/system compromise, and loss of access to the ground stations. The contractor should utilise appropriate processes, workflows, and standards to develop secure software. One starting point may be the Australian Government Information Security Manual[64] [65].

10.1.8.2 Procurement approach aspects

The ground station network is expected to be contributed by GA using existing assets. The development of the tasking interface is low-risk and could be procured internationally or locally with minimal difference. International procurement may increase the risk of a cybersecurity vulnerability and incur greater audit difficulty.

10.1.8.3 Implementation options

A ground station network could be provided in-kind by Geoscience Australia through Australian National Ground Segment Technical Team (ANGSTT), and by USGS through the Landsat Ground Network (LGN). Around 75 contact minutes per day are required to meet the data downlink needs for the mission, which can be achieved with ground stations located in Australia (Alice Springs, ASN) and the US (Sioux Falls, LGS)[66]. Supporting information can be found in Section 11.4.2.

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[63] Angstt.gov.au. 2021. *Network | Australian National Ground Segment Technical Team*. [online] Available at: <http://www.angstt.gov.au/network> [Accessed 22 January 2021].

[64] https://www.cyber.gov.au. 2021. *Australian Government Information Security Manual*. [online] Available at: <https://www.cyber.gov.au/sites/default/files/2021-01/Australian%20Government%20Information%20Security%20Manual%20%28January%202021%29.pdf> [Accessed 22 January 2021].

[65] https://www.cyber.gov.au/. 2021. *Australian Government Information Security Manual - Guidelines For Software Development*. [online] Available at: <https://www.cyber.gov.au/sites/default/files/2020-08/18.%20ISM%20-%20Guidelines%20for%20Software%20Development%20%28August%202020%29.pdf> [Accessed 22 January 2021].

[66] Usgs.gov. 2021. *Landsat Ground Network (LGN) Stations*. [online] Available at: <https://www.usgs.gov/media/images/landsat-ground-network-lgn-stations> [Accessed 22 January 2021].

10.1.8.4 Element cost estimate

The ground station network is assumed to be provided by GA, as an in-kind contribution from USGS, and so incurs no capital expenditure. On-going operating costs for each ground station are assumed to remain constant with additional tasking, hence no operational expense would be incurred.

The development of the tasking interface is expected to cost approximately AUD 0.4M. This figure is comprised of an initial development expense, followed by an on-going operational cost for the lifetime of the mission. Development expenses are not reincurred for future missions, assuming the interface is made available. GA should consider holding a license to use, or ownership of, the interface software for a series of missions. The operational cost is re-incurred for subsequent missions and is predominantly personnel focused. A cost breakdown is provided in section 11.5.2.

10.1.9 Mission management

10.1.9.1 Risk categories

Management of the development of each of the SCR missions would be tailored to fit the specific mission objectives/requirements/metrics, the development schedule, expected cost and the acceptable risks. Currently NASA policy defines proposed space missions a risk classification, A, B, C or D which depends on a variety or programmatic and technical factors. This set of criteria is meant to guide the development of the mission from initial formulation, through execution and final implementation.

This approach enables program managers to develop and implement the proper level of mission assurance and risk management strategies. The mission classification necessarily drives the scope of work across all major activities (e.g. requirements, design, testing, reliability, documentation, and management).

The NASA Procedural Requirements (NPR) framework has defined the four classification levels corresponding to the acceptable risk and project success uncertainty for the development of NASA payloads[67] . A summary of the mission level definitions is given in Table 5.

Table 5 NASA payload development risk classification

	Mission parameters						
Classification	Priority	Complexity	Lifecycle Cost	Risk Tolerance	Mission Life	Launcher Constraints	Alternate Research or Reflight Opportunities
CLASS A	Very high	Very high	High	Lowest	> 5 yr	Medium	None
CLASS B	High	High	Medium to High	Low	5 yr > - > 3 yr	Medium	Few or none
CLASS C	Medium	Medium	Medium to High	Medium	3 yr> - >1 yr	Few	Some or few
CLASS D	Low	Moderate to Low	Medium to Low	High	< 1 yr	Few to none	Many or some

The Class A missions have high national priority, low risk tolerance and very stringent requirements on both project management and technical execution. Examples of Class A missions would be the James Webb Space Telescope or Mars 2020.

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[67] Risk Classification for NASA Payloads, NASA Procedural Requirements NPR 8705.4A, April 21, 2021.

The Class D missions have lower national significance and higher risk tolerance with relatively simple requirements but are easier to execute than Class A missions. NASA has provided a means for innovative payloads and CubeSats to be developed under the Class-C and Class-D designations such that proposals can be created to meet the expectations of NASA project technical, management and cost evaluators[68].

The policy for managing the development of Class D missions allows developers to reduce management overhead and think creatively to meet requirements and maximise larger science returns. Class D missions can also serve as pathfinder missions for more complex, longer life, higher priority missions.

The programmatic impacts of each class of mission are seen in the level of management detail, project structure, systems engineering, quality assurance, testing and verification that is introduced to ensure the mission risk management strategy is properly implemented. The NPR also provides the level of mission assurance that must be implemented and provides guidance in the use of applicable standards and approaches to ensure project success. Elements of each assurance domain (e.g. environmental testing, materials, software) as defined across the risk classifications can be applied as needed to meet the intent of the specific classification that is applied to a project[69].

In addition, program and system engineering requirements can be tailored or customised to the mission risk classification so long as there is consistency and adherence with the accepted risk management[70]. An example would be the consolidation of reviews that would normally be distinct events for a Class C or B mission and focusing more responsibility on the program manger to define resource needs and the project plan. The design, development and verification plans for Class-C and Class-D missions could also differ in the number of models and flight spare hardware that is provided.

The development cost for comparable performance Class-C and Class-D payloads would differ and it is expected that a Class-D mission would cost less than a Class-C mission given the different risk tolerance and complexity levels of each mission. A cost analysis of NASA Class A through D optical remote sensing payloads showed that the median cost per kg for a Class A/B payload was just over $US1000/kg while the median cost for a Class C/D instrument was $US500/kg[71]. Another study of Johns Hopkins University Applied Physics Lab missions showed there is a strong correlation of mission/payload hardware complexity and risk tolerance with the cost for program management, systems engineering and mission assurance functions[72].

The first SCR missions, SCR-1 and SCR-2 are designated Class-D missions while SCR-3 and SCR-4 are designated as Class-C missions. The SCR1 and SCR-2 missions could be managed where consolidation in the areas of testing (to exclude some standard test so long as safety is assured) and systems engineering (use of COTS components and data sheets to serve as ICDs if applicable), and relaxing some reliability requirements is deemed acceptable whereas for SCR-3 and SCR-4 the mission life requirements might mean that this will not be done[73].

Regardless, the management of the SCR missions will be developed in partnership with NASA and USGS so that the mission requirements and instrument performance objectives are met.

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[68] Technical, Management and Cost Panel expectations on SMA-related program requirements for NASA Class C and Class D Payloads, 14 April 2016

[69] NASA Systems Engineering Processes and Requirements, NASA Procedural Requirements, NPR 7123.1C, Feb. 14, 2020.

[70] NASA Systems Engineering Handbook, NASA SP-2016-6105 Rev. 2 (2016).

[71] Mrozinski, J. et al., "NASA Instrument Cost Model: Impact of Mission Class on Cost", NASA Cost Symposium-August 2016, Jet Propulsion Laboratory, California Institute of Technology (2016)

[72] Hahn, M., "Higher fidelity estimating: Program management, systems engineering and mission assurance", NASA Cost Symposium August 25, 2015, NASA Ames Research Center (2015).

[73] Wells, J, at al., "Class D management implementation approach for the first orbital mission of the Earth Venture series", Proc. SPIE 8866, Earth Observing Systems XVIII, 88660C (23 September 2013);

10.1.9.2 Project Life Cycle Phases

The NASA project life cycle concept is a fundamental tool for the management of the formulation and implementation of major systems and categorises activity and deliverables into project distinct phases. This approach would be implemented in the development of the SCR and adapted to the mission class for each SCR (e.g., SCR-1 and SCR-2 as Class D; SCR-3, SCR-4 and/or MMI SCR as Class C).

A summary of the project development phases excluding operations and disposal is given in Table 6 as a reference.

Table 6 NASA Project life cycle phase

NASA Project Life Cycle Phases	**Pre-Phase A**	**Phase A**	**Phase B**	**Phase C**	**Phase D**
Major Activity	Mission requirements and technology development	Mission and system architecture development, ConOps definition, risk assessments and requirements finalisation	Complete technology development, prototyping and risk-mitigation strategies	Complete detailed design and manufacture component and subsystem parts	Complete system manufacturing, assembly, integration and test; Prepare for launch
Project Milestones	End user consultation; Mission goals determined; Conceptual designs and feasibility assessments;	Requirement refinement, performance and functional analyses; Trade-off studies to consider validity of system design options; Cost and schedule analyses; Develop breadboard and engineering units	System technical baseline refinement includes system and subsystem H/W and S/W requirements, specifications, ICDs, designs, verification and test plans; GSE designs	Complete 'build-to' specifications, ICDs and final product design; Engineering units are built and tested	Complete qualification, verification and validation, end-to-end tests and assess/approve test results; delivery of product
Project Reviews	Culminates in MCR	Culminates in systems SRR	Culminates in system PDR	Culminates in system CDR	Culminates in system LRR
Supporting Reviews		Subsystem SRRs	Subsystem PDRs	Subsystem CDRs	System and subsystem TRR and System FRR
Key documents (examples)	Preliminary versions of Mission Objectives, ConOps, ROM cost, schedule and risk plans, Technology Development Plan and SEMP	Baseline versions of WBS, work packages and SOWs, PMP , SEMP and DDVP and Control & Specialty engineering plans	Baseline System and subsystem performance budgets, specifications, ICDs and test and specialty engineering plans; Long Lead Item List, Preliminary Configuration Item Data List	Detailed/final system and subsystem design plans, specifications, ICDs, AIT and Environmental test plans, manufacturing, validation and verification plans; final model (e.g. structural, thermal)	Final test and readiness reports

10.1.9.3 Project management planning

The Phase A development of SCR would be guided by a Project management Plan (PMP) that is followed by the project team. The PMP will outline the approach for project execution, the project milestones and deliverables that are required throughout all phases of the project.

10.1.9.4 Organisation

The organisational approach would be to form an integrated product team (IPT) that will perform all activities to fulfil the assigned tasks and deliver the product. The IPT will be led by a Project Manager (PM) who has direct responsibility for project direction and coordination, subcontractor management, definition of tasks and allocation of resources, ensures project contractual obligations are met, provides progress, scheduling, and cost control, directs reporting and is the primary point of contact for the Customer.

Depending on the prime contractor for SCR the organisation could also include a Contract Officer and Project Controller who are responsible for all contractual and project control functions. Although some of these tasks could be assigned to the PM.

A lead Systems Engineer (SE) or Project Engineer would be the technical responsible for directing and managing all the engineering and technical activities of the project. The SE defines the Work Breakdown Structure and develops the work packages that define the scope, cost, and schedule of technical activities. Domain Engineering Leads would be assigned for the key engineering disciplines within the project (e.g. mechanical, thermal, software, electrical, optical, AITV etc) and would provide the necessary subsystem and specialist skills to execute the work.

The project could also support a Product Assurance (PA) or Quality Assurance (QA) Manager who oversees all quality aspects of the program and works closely with the PM and SE to assist and advise on quality control and assurance matters. Although some responsibilities could be assigned to both the SE and PM if needed.

An Operations Manager (OM) is assigned to lead all manufacturing, assembly, integration, and test activities for the project. This role could also be assigned to the lead AITV engineer.

A subcontracts manager could be assigned to manage all contracts with external suppliers although this role could be divided between the PM and PA managers.

10.1.9.5 Communications and Control

Internal and external interface/communication management would be agreed at the start of the program and included in the PMP. A well-defined approach ensures that miscommunication is minimised, and program efficiency is preserved. Correspondence and document management become important, and the project could support a communication and document control manager to ensure adherence with the agreed approach.

Reporting across the project organisation is a crucial activity and is essential to ensure project success. Typically, these lines of reporting are defined before project kick-off and are defined in the PMP. Internal reporting includes communications through meetings, document exchange and status reports as well project level meetings such as design and test reviews. The PM directs all project level meetings within the IPT. Customer reporting can occur through regular project meetings, progress reports including critical items and milestones.

Reporting frameworks are constructed to cover management, contract, schedule, cost, technical progress, parts procurement, and supplier contract as well as product assurance issues.

10.1.9.6 Documentation

A document management approach would be defined to cover program requirements, Documents would be formatted, coded, referenced, archived, and classified in compliance with the project requirements. Consistency in the production of project documents is a critical activity and all documents should be categorised and included in a project document list indicating their status.

Time and schedule savings can be gained by streamlining document control without sacrificing technical or programmatic adherence to requirements. For example, in a Class D program a supplier data sheet for a part can be used, if deemed suitable, instead of creating a specific ICD for the use of that component.

Key documents that would be delivered in baseline form shortly after kick-off on any SCR project would include a Program Management Plan (PMP), WBS and Product Tree, Systems Engineering Management Plan (SEMP), Risk Management Plan (RMP), Master Schedule, Design, Development and Verification/AIT Plan (DDVP), Configuration Management Plan (CMP), Component Control Plan, Deliverable Items List (includes product hardware and software deliverables), Deliverable Document List (includes contract regulated reports, plans, data packages, analyses, models, lists of components, parts, processes and materials, engineering documents, schedules, specifications, manuals, drawings, diagrams, ICDs, ConOps documents, processes and procedures), and Customer Furnished Item List.

10.1.9.7 Configuration management

A configuration management system should be established to maintain the product baseline and keeps track of revisions and versions to ensure changes are tracked and the current embodiment of the product is clearly identified and known to all members of the IPT, external suppliers where needed and the Customer. A Configuration Control Board (CCB) should be established to review, analyse, and accept or reject proposed changes and/or waivers to the baseline. The CCB should include the PM, SE, and PA/QC manager at a minimum.

An inventory list should also be established that identifies Customer owned property acquired by the prime contractor or furnished by the Customer and is controlled in accordance with the project statement of work and contract.

10.1.9.8 Risk management

A risk management policy/plan should be established early in the project and refined throughout the project life-cycle. The scope of the plan is the early and continuous identification of risk areas, their classification and control using suitable mitigation strategies. A risk register should be established to track and update status of identified project risks and reported through established communication methods.

10.1.9.9 Design, development, and verification

For spacecraft a design, development, and verification plan (DDVP) describe the engineering activities throughout the project and includes the model philosophy, AIT activities/sequences at subsystem and system levels, qualification strategies as well as final integration activities in the launch vehicle. The DDVP is typically developed by the end of Phase A and updated throughout the project and is included in the project deliverable items list.

Product critical items are identified in the Phase A and Phase B activities of a project. These may be items that have a high degree of engineering complexity, design risks or procurement risk (i.e. long lead items). Mitigation of the risks associated with critical items is part of the risk management plan.

The qualification approach for the payload and spacecraft are created to validate the design and build activities as well as to reduce risk to critical components and subsystems.

The DDVP for SCR development will probably change depending on the instrument to be flown. For example, SCR-1 might follow a payload model approach where only one spectrometer unit is procured and is subjected only to acceptance level vibration and thermal conditions to avoid excess stress on this hardware.

The project model philosophy for subsystems and system levels would be decided based on the mission requirements. For example, the MMMI project might follow a model approach where various structural, thermal, and engineering models are built to validate the designs of bespoke or custom hardware that might be needed to meet the full operational capability requirements. Whereas for less complicated missions such as SCR 1-2 the number of models might be reduced especially if the subsystems have flight heritage or are procured (e.g., headwall spectrometer unit).

10.1.10 Notional SCR-1 project schedule milestones

The development approach to the SCR-1 which serves as a pathfinder for the fully operational SCR would be implemented so that launch would roughly coincide with the deployment of CLARREO-PF in Q4 2023. This mission would use a hyperspectral imaging spectrometer from Headwall or similar to that instrument development time would be kept be minimised. Several approaches could be implemented to reduce schedule and risk for this Class D mission. For example, long lead items could be procured as early as practical rather than waiting until after a CDR. ICDs for the spectrometer could be simplified by working with the manufacturer from an early stage in the project.

A notional 33-month schedule for SCR-1 is provided in Table 7.

Table 7 Notional development schedule for SCR-1

NASA Project Life Cycle Phases		*Pre-Phase A/ Phase A*				*Phase B*				*Phase C*						*Phase D*																		
		2021									2022												2023											
		Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
SCR-1 Project Milestones		A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Kickoff	T0	◆																																
System Requirements Review (SRR)	T0+3				◆																													
Preliminary Design Review (PDR)	T0+7								◆																									
Critical Design Review (CDR)	T0+13														◆																			
Manufacturing Readiness Review (MRR)	T0+16																	◆																
Test Readiness Review (TRR)	T0+28																										◆							
Flight Readiness Review (FRR)	T0+32																																◆	
Launch Readiness Review (LRR)	T0+33																																	◆
Launch	T0+33																																	◆

10.1.11 Procurement and tender concepts

The primary objective is to develop an EO solution that meets Australia's commitments to the Global Observing System; but a vital secondary policy objective is to support the sustainable development of Australia's space industry. Deloitte Access Economics has performed a detailed economic study of the Australian EO sector to support the development of the EO Roadmap[74] . This report highlights the significant benefits of tailoring a procurement approach that delivers the specified mission capabilities but also provides a means to fulfil secondary objectives such as the promotion of Australian space and general industry growth, commercialisation of research and development outcomes, upskilling and developing a space industry workforce, enhancing regional development and increasing export readiness.

One of the key outcomes for Australia's investment in the SCR mission is the associated development of the domestic space industry capability and involvement of domestic organisations in the project. The report states:

> *"This delivers a number of benefits for Australian organisations, including sustainable demand, mentoring and knowledge transfer (from primes), flight heritage and opportunities for new business connections. This includes provisions around industry content measured at the subsystem level and whether components have been made or assembled on home soil."*

The Deloitte report also highlights that by procuring the design, manufacturing and, potentially, launch of small satellites within Australia, the SCR mission can use government demand to underpin growth in the domestic space industry supply chain.

> *"In addition, the benefits to Australia of incorporating secondary policy objectives into a procurement approach which will by necessity require the use of innovative contracting and procurement processes whilst adhering to best-practice risk management guidelines."*

For example, NASA has provided a means for developing innovative payloads and CubeSats under the Class-C and Class-D mission designations such that proposals can be created to meet the expectations of NASA project technical, management, risk and cost evaluators. In any approach, consideration must be given as to how to deliver on the strategic objectives of the mission while still delivering value for money.

The Deloitte report provides several suggestions and guidelines for developing a suitable approach for the SCR program. These include:

- Investigating the necessary regulatory settings required to support an ongoing, long-term investment that can provide industry with confidence to invest.
- Exploring how to build a program that manages innovation cycles where a tender process has an in-built tolerance of risk and acceptance of failure.

This approach is acceptable for a Class-D mission procurement. For example, SCR launching two satellites every two years serves to de-risk the investment and can allow time for innovation and

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[74] "Economic study into an Australian continuous launch small satellite program for Earth observation", Deloitte Touche Tohmatsu Ltd. (2021) https://www2.deloitte.com/au/en/pages/economics/articles/economics-earth-observation.html

experimentation between launches - while also allowing time for evaluation and generational development. These approaches are essential to lifting domestic organisations up the technology readiness maturity curve and ensures the program will have flexibility and rigour such that it can learn from failures and spread this knowledge across the space industry community.

It is typical in many space missions that multiple tenderers are engaged in the early phases of a programme through Phase A, and perhaps into Phase B, thereby enabling the program sponsor to evaluate multiple organisations and proposals to participate in the design process and arrive at a robust design solution.

Alternatively, taking a consortium approach to tendering with inputs from multiple partners and suppliers. This would be managed by a systems integrator who ideally provides legal, financial, insurance and even warehousing support.

The Deloitte report also advises that a tailored tendering process be adopted to meet industry requirements that can facilitate the definition of program management processes early on to ensure efficiency, clarity and review are well articulated and understood.

Procurement of both standard and unique parts would be conducted in accordance with the project approved specifications. Components should be procured from qualified suppliers where possible. A Component Control Plan (CCP) should be used for both co-ordinated and self-procured parts as it formulates the parts procurement approach that will be used on the project.

Purchasing of COTS components is allowed on a Class D mission (SCR-1 and SCR-2) but there should be an established approval process to ensure the highest possible reliability and to understand the inherent project risk in using such components.

Unique parts that will be self-procured must undergo a valid and acceptable qualification test activity. This project requirement can assess the suitability of the design and application of the part, the standards of fabrication and assembly, the materials and treatment processes as well as to identify possible failure modes. An example of a unique part for the SCR 1-2 could be the spacecraft platform or chassis. A custom-made CubeSat - for example that accommodates the SCR 1 Headwall payload and other subsystems - would be fabricated, treated and tested by a supplier and as such is a unique and critical part of the final product.

With the above considerations in mind one potential procurement approach would be to use three tenders:

- Tender 1: covering SCR1-4
- Tender 2: covering a MMI pathfinder which could be described as AquaWatch
- Tender 3: covering MMI1-4
- Tender n: covering the next four MMI satellites

Within each of these tenders, similar evaluation criteria could be used but with different weighting, for example a potential list of evaluation criteria could include:

- Ability to deliver breakthrough specification
- Ability to deliver target specification
- Risk
- Cost
- Australian industry content
    - % of each subsystem designed in Australia
    - % of each subsystem manufactured in Australia
    - % of each subsystem assembled in Australia
    - % of each subsystem tested in Australia

10.2 MMI summary

The AquaWatch and OzFuel Australian Earth observation systems are both in their initial concept design phases. These missions provide context for the possible development of a multi-mission hyperspectral sensor that would also meet the needs of future SCR missions.

During this study, the stakeholders developed a set of payload requirements that would meet the maximum number of mission objectives of the SCR, AquaWatch and OzFuel missions. Key stakeholders from GA, ANU, CSIRO and SmartSat CRC participated in this process. These requirements are summarised In Table 11.

The MMI mission development costs have been estimated using inputs and results from this study, by comparing the costs to develop science grade HSIS such as EnMap and PRISMA as well as knowledge of high-performance EO instruments which are similar in complexity to an envisioned Multi-mission system. A cost comparison was also made with the estimated costs of other Australian mission concepts namely AquaWatch and OzFuel.

The Multi-mission spacecraft is highly likely to be a 100-250 kg smallsat which will provide the required pointing, mechanical and thermal stability and station keeping capability. A spacecraft bus such as the RocketLab Electron can carry up to 200 kg into a SSO at approximately 550 km altitude. An estimated cost for a dedicated Electron launch is ~ AUD 6.5M. A spacecraft bus such as the RocketLab Photon can accommodate a MMI and other spacecraft subsystems and would cost ~ AUD 13M.

The MMI will be sized to provide the needed optical throughput to meet the SNR requirements across the various missions. An MMI telescope aperture diameter will likely be on the order of 200-400 mm. The MMI will likely be mounted on a dedicated optical bench to provide the needed mechanical and thermal stability. These design aspects will necessarily lead to larger instrument volume and mass and a subsequent increase of the instrument development cost.

The MMI development costs have been estimated using inputs and results from this study, by comparing the costs to develop science grade spectrometers such as EnMap and PRISMA as well as knowledge of other high-performance EO instruments which are similar in complexity to an envisioned MMI and finally a comparison to the estimated costs of other Australian mission concepts namely AquaWatch and OzFuel.

NASA's Office of Independent Program and Cost Evaluation (IPCE) has established initiatives to improve its cost and schedule estimating capabilities. To support this activity the Jet Propulsion Laboratory (JPL) has developed the NASA Instrument Cost Model (NICM) for both planetary and Earth observing instruments across specific regions of the electro-magnetic spectrum. NICM is a cost and schedule estimator that contains a system level cost estimation tool that is based on instrument mass and total power consumption; a subsystem level cost estimation tool; a database of cost and technical parameters of more than 140 previously flown remote sensing and in-situ instruments[75]. NICM also includes a schedule estimator and a set of rules to estimate cost and schedule by life cycle phases (B/C/D) based on the historical record of successful NASA instrument missions.

NICM has gone through several revisions over the years. A system level regression formula for planned optical Earth observation missions can be used to estimate the cost of developing an instrument from development in Phase B to completion at the end of Phase D. JPL is also developing estimating tools for each class of NASA missions A – D.

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[75] Habib-Agahi, H., et al.," NASA instrument cost/schedule model", 2011 IEEE Aerospace Conference, Big Sky, Montana March 5-12, 2001. http://hdl.handle.net/2014/4774

An estimate of MMI instrument development cost can be produced using the NCIM estimator based on projected mass and power consumption for MMI. A MMI mass estimate of 51 kg and a maximum power consumption estimate during imaging operations of 76 W was obtained by comparing an MMI configuration with other EO instruments of similar complexity and performance. Using the NICM VII regression formula[76] an instrument cost estimate of USD 36.9 M was obtained. Applying a current exchange rate results in an MMI instrument cost estimate of AUD 49.4M.

The provisional cost estimate from the Study for the **MMI system is AUD 75-100M**.

Another estimate which combines the NICM MMI instrument cost estimate with the provisional estimates for other mission segments yields a mission cost estimate between AUD 81M and AUD 97M which is provided in Table 8. Specific known uncertainties are covered by a local margin. For all other elements that show a margin of 0%, the uncertainty is covered through the 20% margin applied at the highest level.

The margins apply to the line in which they are listed. This means that the *Cost without any margin* column always lists each element's cost as derived if not considering any lower-level margins. The *ROM cost* column on the other hand applies the listed margin to the sum of the lower-level *ROM cost* (including the lower-level margin).

The MMI project model philosophy for subsystems and system levels would be decided based on the mission requirements. For example, MMI might follow a model approach where various structural, thermal, and engineering models are built to validate the designs of bespoke or custom hardware that might be needed to meet the full operational capability requirements. Whereas for less complicated missions such as SCR 1-2 the number of models might be reduced especially if the subsystems have flight heritage or are procured (e.g., COTS spectrometer unit). There will likely be increases to the MMI mission cost presented here which will depend on the design, development and validation philosophy that is adopted on a future programme

Admittedly, more work is needed to codify the overall concept of operations, refine the mission and space segment requirements and perform a detailed MMI concept design to refine this estimate. This would be a goal of a future Phase A study.

Table 8 ROM cost estimate for a single MMI mission

Element	Cost without any margin (AUD M)	Margin (locally applied)	ROM cost (AUD M)
Multi-mission Imager	**81**	**20%**	**97.2**
Ground Segment	1	0%	**1**
Launcher (e.g. RL Electron; max 200kg to 550 km SSO))	6.5	10%	**7.15**
Mission Operations Centre	4.1	0%	**4.1**
Processing pipeline	1.6	0%	**1.6**
Satellite	67.8	0%	**79.96**
Environmental Qualification	1	20%	**1.2**
Integration + System-level Tests	3	20%	**3.6**
NICM VII estimate for Payload	49.3	20%	**59.16**
On ground Payload Calibration	1.5	100%	**3**
Platform / Bus (e.g. RL Photon)	13	0%	**13**

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[76] https://www.nasa.gov/sites/default/files/files/14_NICM_VII_for_2015_NASA_Cost_SymposiumFinal_tagged.pdf

11 Analyses

This chapter provides detailed analyses performed during the study or evidence supporting high level information provided in the previous chapters of this report. The following sections have a loose top-down order, but should be considered as independent chapters to be read in conjunction with the associated sections of this report.

11.1 Systems engineering analyses

11.1.1 Requirement analysis

A core part of the CDF activity consisted of a derivation of mission requirements from the customer's needs, although further refinement with the USGS is ongoing. This section outlines the various levels of requirements identified in this process.

The following sets of requirement specifications have been defined at this stage:

- **Mission objectives** as stated by the customer (USGS and NASA) for a full operational capability
- **Instrument specification** as derived from the mission objectives and technical analyses into the required performance
- **Spacecraft platform requirements** as derived from the instrument specification to inform a small RFI campaign directed toward satellite bus and subsystem providers
- **Pathfinder mission descoped objectives** to specify any areas in which the pathfinder mission may deviate from the full operational capability missions and identify changes to the space segment requirements

Their hierarchical relationship in simplified format is depicted in Figure 7. The individual requirements for each specification are further detailed in the subsequent sections.

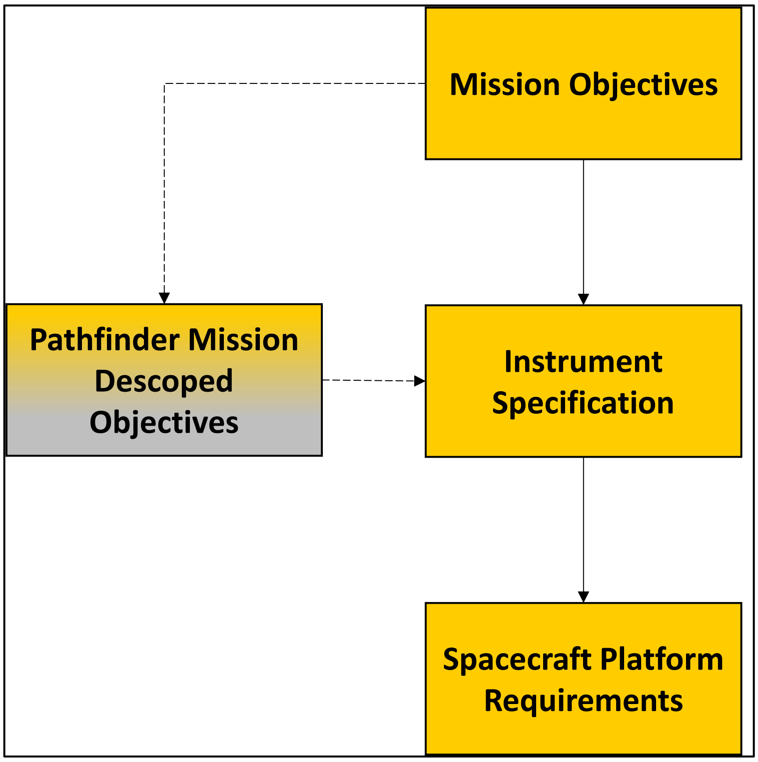

Figure 7 SCR mission specification hierarchy

11.1.1.1 USGS initial requirements

The initial set of SCR performance capability and background requirements came from the USGS and was presented at JACIE 2019 [77] . A summary of these requirements from USGS is presented in Table 9.

Table 9 USGS SCR specification presented at JACIE 2019

Requirement		**Specification**
Spatial	Spatial resolution -GSD (m)	
	VNIR/SWIR	100
	TIR	300
	Swath-all bands (km)	60
Spectral	Spectral range (nm)	
	VNIR/SWIR	400-2400
	TIR	TBD
	Centre wavelength spacing (nm)	
	VNIR/SWIR	5
	TIR	5
	Number of bands	
	VNIR/SWIR	400
	TIR	TBD
	Spectral resolution (FWHM) - $\Delta\lambda$ (nm)	
	VNIR/SWIR	8
	TIR	TBD
Radiometric	Radiometric resolution	
	NEDL (mW-m^{-2}sr^{-1}nm^{-1})	TBD
	NEDT (K)	0.15
	Radiometric accuracy	
	VNIR / SWIR (%)	1
	TIR (K)	0.3
	Signal-to-Noise Ratio	300:1

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[77] Christopherson, J., "An SLI Cross-calibration Radiometer 9SCR) concept for improved calibration of disaggregated Earth observation satellite systems", 2019 JACIE Workshop, Reston, VA, USA., 24-26 Sept. 2019

11.1.1.2 Australian SCR requirements

These payload performance requirements were expanded during the study to form a “first-order’’ specification for an Australian produced SCR. The parameters presented in Table 10 are the result of the iterative discussions with key stakeholders during and after the study, including USGS personnel, as well as assessments of technical feasibility within an Australian context subject to the perceived constraints of the mission. The resolution requirements for spatial, spectral and radiometric performance would be refined in a future Phase A study. The values presented here have been informed by and would follow accepted user-community definitions for these key system performance metrics. [78], [79], [80]

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[78] https://esto.nasa.gov/files/SLIT2015/RMAKeyParameters.pdf

[79] NASA-SLI-001 Land Imaging Requirements Rev B

[80] Ryan, R., Pagnutti, M. and Christopherson, J., “Satellite Cross-calibration radiometer (SCR): Specification”, presented at USGS/GA Technical Interchange Meeting, 6 July 2021.

Table 10 Australian SCR specification

Requirement		Breakthrough Specification	Target Specification
Spatial	Spatial resolution -GSD (m)		
	across-track (nadir)	100	100
	along-track (nadir)	100	100
	Swath (km)-nadir	40	60
	Spatial resolution		
	Edge slope (m^{-1})	≥ 0.0073	≥ 0.0073
	Aliasing (GSD / Edge slope)	≤ 0.9	≤ 0.9
	Half-edge extent	< 88 m (VNIR); < 107 m (SWIR)	< 88 m (VNIR); < 107 m (SWIR)
Spectral	Spectral range (nm)	400-2400	350-2400
	Spectral sampling interval (nm)	10	5
	Number of bands (max)	200	410
	Spectral resolution (FWHM) - $\Delta\lambda$ (nm)	15	7.5
	Spectral calibration accuracy (nm)	0.1	0.1
	Centre wavelength cross track variation (nm)	0.1	0.1
Radiometric	Radiometric resolution ($mW\text{-}m^{-2}sr^{-1}nm$)	0.01	0.01
	Radiometric accuracy (%)		
	Pre-flight	3	2
	On-orbit	5	3
	Radiometric stability (%) over 30 days	0.2	0.2
	Signal-to-Noise Ratio	> 150:1	> 150:1
	Dynamic range - ADC (bits)	12	12
Other	Orbit		
	Type	Polar-SSO	Polar-SSO
	Altitude (km)	550-705	550-705
	Daily collection volume (GByte)* - uncompressed	117	360
	Data compression	Lossless (2:1)	Lossless (2:1)
	Ancillary bus data	Orbit, attitude, GPS, timing	Orbit, attitude, GPS, timing
	Ancillary P/L data	Configuration, thermal	Configuration, thermal
	Downlink band	X band	X or KA band, or laser
	Program risk classification (NASA)	Class D	Class C

* Assumptions: "SSO 645 km; T = 97.76 min., Vssp ~7530 m/sec--> tint = 0.0133 sec.; Duty cycle = 0.15; image land only on sunlit portion of orbit; Daily collection vol = # Xtr spatial samples*# In track spatial samples*#spectral bands*ADC*orbits/day*byte/8 bits"

11.1.1.3 Australian MMI hyperspectral sensor requirements

The AquaWatch and OzFuel Australian Earth observation systems are both in their initial concept design phases. These missions provide context for the possible development of a multi-mission hyperspectral sensor that would meet the requirements for water-body quality monitoring and bushfire detection as well as meeting the cross-calibration mission requirements of future SCR missions. During this study, the stakeholders developed a set of payload requirements that would meet the maximum number of mission objectives of the SCR, AquaWatch and OzFuel missions. Key stakeholders from GA, ANU, CSIRO and SmartSat CRC participated in this process.

The parameters presented in Table 11 are the result of the iterative discussions with key stakeholders during and after the study, including USGS personnel, as well as assessments of technical feasibility within an Australian context subject to the perceived constraints of the mission. The resolution requirements for spatial, spectral and radiometric performance would be refined in a future Phase A study. The values presented here have been informed by and would follow accepted user-community definitions for these key system performance metrics.

Table 11 Australian MMI hyperspectral smallsat specification

Requirement		Breakthrough Specification	Target Specification
Spatial	Spatial resolution -GSD (m)		
	across-track (nadir)	30	30
	along-track (nadir)	30	30
	Swath (km)-nadir	40	60
	Spatial resolution		
	Edge slope (m^{-1})	≥ 0.0243	≥ 0.0243
	Aliasing (GSD / Edge slope)	≤ 0.9	≤ 0.9
	Half-edge extent	< 24 m (VNIR); < 29 m (SWIR)	< 24 m (VNIR); < 29 m (SWIR)
Spectral	Spectral range (nm)	400-2400	350-2400
	Spectral sampling interval (nm)	10	5
	Number of bands (max)	200	410
	Spectral resolution (FWHM) - $\Delta\lambda$ (nm)	15	7.5
	Spectral calibration accuracy (nm)	0.1	0.1
Radiometric	Centre wavelength cross track variation (nm)	0.1	0.1
	Radiometric resolution (mW-$m^{-2}sr^{-1}$nm)	0.01	0.01
	Absolute radiometric accuracy (%)	2	2
	Pre-flight	3	2
	On-orbit	5	3
	Radiometric stability (%) over 30 days	0.2	0.2
	Signal-to-Noise Ratio	200:1	200:1
	Dynamic range - ADC (bits)	12	12
Other	Orbit		
	Type	Polar-SSO	Polar-SSO
	Altitude (km)	550-705	550-705
	Daily collection volume (GByte)* - uncompressed	1300	4000
	Data compression	Lossless (2:1)	Lossless (2:1)
	Ancillary bus data	Orbit, attitude, GPS, timing	Orbit, attitude, GPS, timing
	Ancillary P/L data	Configuration, thermal	Configuration, thermal
	Downlink band	X band	X or KA band or laser
	Program risk classification (NASA)	Class C	Class C

* Assumptions: "SSO 645 km; T = 97.76 min., Vssp ~7530 m/sec--> tint = 0.0133 sec.; Duty cycle = 0.15; image land only on sunlit portion of orbit; Daily collection vol = # Xtr spatial samples*# In track spatial samples*#spectral bands*ADC*orbits/day*byte/8 bits"

11.1.2 Mission objectives

The following mission objectives have been identified through iterative discussions with the customer:

Table 12 SCR mission objectives

ID	Title	Description
SCR-MIS-001	Cross-Calibration	Collect coincident spectral radiometer data between cooperative optical satellite missions for cross-calibration
SCR-MIS-002	Orbit	Either: LEO optimised for cross-calibration with TBD cooperative missions Or: SSO trailing (by 20min max) one leading S/C which is one of (in order of priority): 1) Landsat, Sentinel 2 2) Planet Super Doves 3) Every other optical EO mission
SCR-MIS-003	Continuous launch	Continuous launch with annual fix funding Goal: 2 Satellites every 2 years
SCR-MIS-004	Instrument	First: Supplied through USGS (as an option) Subsequent: TBD
SCR-MIS-005	Manufacturing policy objective (bus)	Australian built
SCR-MIS-006	Manufacturing policy objective (instrument)	Hyperspectral instruments leveraging Australian niche capability Series of configurations
SCR-MIS-007	Launch date	Q4 2023 to coincide with CLARREO Pathfinder
SCR-MIS-008	Design lifetime	2 years (B), 5 years (T)
SCR-MIS-009	Operations concept	Contractors operating out of the GA facility in Symonston, ACT to enable increased cyber security implementation

11.1.3 Observation requirements

Based on the above mission objectives, the mission observation requirements for the operational SCR mission have been derived. The results presented in Table 13 below are based on iterative discussions with key stakeholders from customer side and assessments of technical feasibility within the programmatic constraints for the mission. The table also lists a rationale for each requirement or a parent requirement from which it was derived.

Table 13 SCR observation requirements

ID	Title	Text	Rationale	Parents
SCR-OBS-0001	GSD VSWIR	100m	10m for AW, OzFuel 100m for USGS	SCR-MIS-001
SCR-OBS-0002	Relative orbit (if applicable)	Coincident observation +-20 minutes	To reuse same ground station To enable cross-calibration Target missions in priority order: Landsat-8, Sentinel-2A, Landsat-9, Sentinel-2B, Super Dove	SCR-MIS-002
SCR-OBS-0003	Georeferencing accuracy	Image data shall be geo-referenced to within 1x GSD.		SCR-MIS-001
SCR-OBS-0004	Simultaneous imaging and downlink	Spacecraft shall be able to perform imaging while downlinking payload data.	To enable imaging in typical calibration sites near ground station locations.	SCR-MIS-001
SCR-OBS-0005	Configurable payload operations	The payload operations shall allow for selecting a subset of the instrument's spectral bands to be downlinked only.	To reduce downlink data rate requirement. But it is not a desirable operational mode to account for not-yet-known applications needing specific band data.	SCR-MIS-006, SCR-MIS-004
SCR-OBS-0006	Swath location	During observations, the swath shall be completely within the reference mission's swath.		SCR-MIS-001, SCR-MIS-002
SCR-OBS-0007	Swath width VSWIR	20-60km		SCR-MIS-001
SCR-OBS-0008	Spectral range VSWIR	400nm - 2400nm		SCR-MIS-001
SCR-OBS-0009	Number of bands VSWIR	100-400		SCR-MIS-001
SCR-OBS-0010	Band width VSWIR	8nm-12nm FWHM		SCR-MIS-001

ID	Title	Text	Rationale	Parents
SCR-OBS-0011	Radiometric accuracy VSWIR	1% to 2%		SCR-MIS-001
SCR-OBS-0012	SNR VSWIR	100-300 varying over spectral range, details are TBC		SCR-MIS-001
SCR-OBS-0013	Radiometric stability VSWIR	<0.2% over 30days		SCR-MIS-001
SCR-OBS-0014	Imaging duty cycle	Perform coincident observations and Cal/Val sites (B) Image all land area during daylight (T)		SCR-MIS-002, SCR-MIS-001

11.1.4 Preliminary platform requirements

Preliminary satellite platform requirements have been derived from the observation specification to support a preliminary RFI campaign among satellite bus manufacturers. It should be noted that values for the requirements have not been derived through a generic technical assessment. They rather represent an expected envelope based on the needs of a sensor (see section 11.3.3 for more details). It is therefore possible that not all observation requirements listed above are able to be fulfilled with a satellite bus as specified in Table 14.

Table 14 Preliminary blackbox platform requirements

ID	Title	Text	Rationale	Parents
SCR-PF0-0001	Payload Dimensions	>200mm x >300mm x >300mm		SCR-OBS-0001, SCR-OBS-0007, SCR-OBS-0008
SCR-PF0-0002	Payload Mass	>15kg		SCR-OBS-0001, SCR-OBS-0007, SCR-OBS-0008
SCR-PF0-0003	Payload Power	>40W orbit average		SCR-OBS-0001, SCR-OBS-0011, SCR-OBS-0012, SCR-OBS-0010, SCR-OBS-0004
SCR-PF0-0004	Pointing control accuracy	60 arcsec (goal), 150 arcsec (threshold)		SCR-OBS-0003
SCR-PF0-0005	Pointing knowledge	Driven by pointing control		SCR-PF0-0004
SCR-PF0-0006	RF payload downlink frequency	X-band	Required to achieve downlink data rates	SCR-OBS-0004

ID	Title	Text	Rationale	Parents
SCR-PF0-0007	Payload downlink data rate	760Mbps (goal), 200Mbps (threshold)		SCR-OBS-0007, SCR-OBS-0001, SCR-OBS-0009, SCR-OBS-0002, SCR-OBS-0004
SCR-PF0-0008	On-board payload data storage	320GB (goal), 120GB (threshold)		SCR-OBS-0007, SCR-OBS-0001, SCR-OBS-0009, SCR-OBS-0002
SCR-PF0-0009	Propulsion delta-V	>100m/s	Station keeping Deorbit	SCR-OBS-0002

11.1.5 Pathfinder mission descope options

Finally, a key question addressed during the study was the level to which the SCR pathfinder missions shall de-risk the FOC missions. The result of this assessment is the list of acceptable descoping items presented in Table 15. Note that a pathfinder mission may accept any subset of the listed items to achieve the mission objectives.

Table 15 Areas of descope of the pathfinder mission

ID	Description
SCR-PFD-0001	The SCR pathfinder mission may provide only a subset of the observable land areas. I.e. there is no need to image and downlink every accessible location.
SCR-PFD-0002	The SCR pathfinder may perform cross-calibration by crossing passes with the reference mission; there is no need to fly in the same orbit.
SCR-PFD-0003	The SCR pathfinder may only perform imaging when coinciding with a reference mission.
SCR-PFD-0004	The SCR pathfinder mission may only create one global, annual, cloud-free mosaic of observed data.
SCR-PFD-0005	Consider reducing radiometric accuracy to 3-5 %
SCR-PFD-0006	Consider Headwall Micro-HyperSpec (space qualified) option for SCR1-2 to achieve low-risk, fast-launch profile
SCR-PFD-0007	Remove need to image at the same time as downlinking payload data
SCR-PFD-0008	Consider a reference mission orbit of < 600km altitude and no on-board propulsion
SCR-PFD-0009	Consider 1 year mission life (consistent with Class D mission)

11.1.6 Trade-offs

At this early stage of the SCR mission design, several key trade-offs have been identified. Not all of them have been assessed at this stage.

- Orbit selection (linked to reference mission selection)
- Instrument design / COTS option
- Propulsion
- Number of star trackers
- Spacecraft mass range / form factor
- Payload data downlink RF band
- Spacecraft antenna concept
- Ground station locations and size
- Test model philosophy
- MOC operation staffing
- Include lateral off-nadir pointing in ConOps (as goal only)

The first 10 of the above trade-offs have been considered together for the SCR pathfinder mission. I.e. three combinations of the individual options have been created to identify a baseline system concept for the pathfinder mission. This is described in more detailed in the following section.

11.1.6.1 Pathfinder system concept trade-off

The SCR pathfinder mission can be implemented in various ways depending on the specific requirements to be descoped from the FOC mission (see sec 11.1.5). Table 16 provides three options for what an implementation of the pathfinder mission could look like based on preliminary technical assessment of the combination of different trade-off elements. The selected baseline is marked in green with a simpler version and a more performant option provided for reference.

Table 16 Pathfinder implementation trade-off

Trade-off element	Reduced scope	Baseline for PF	Step-up towards FOC	Other options
Reference mission / ROM altitude	Super Dove / <600km	Landsat / 700km	Sentinel 2 / 800km	Other / <600km
Instrument	Similar to Headwall Micro HyperSpec	Similar to Headwall Micro-HyperSpec	Ball CHPS, Custom-built	
Propulsion	No propulsion	Electrical or cold gas	Electrical	Chemical mono-propellant Chemical bi-propellant
Star tracker	1	3	3	0, 2
Form factor / mass	16U	30kg – 50kg	~100kg class	12U Photon-type
PL data downlink	X-band	X-band	X-band	S-band Ka-band Optical
S/C antenna concept	Single patch	Antenna array	Antenna array	Single patch Gimballed
Ground stations	Alice 9m	Alice 9m + USA	Alice 9m + USA	See sec. 11.4.2
System hardware models	FlatSat, SM, TM, EQM, FM	FlatSat, SM, TM, EQM, FM	FlatSat, SM, TM, EQM, FM	EM (Engineering model) PFM (Proto-flight model)
MOC operations	Business hours	Business hours	Business hours or As needed	Fully automated after handover 24/7 operations

11.1.7 Risk assessment

Risk assessments are a standard processes in a NASA Pre-Phase A study as per the NASA System Engineering Handbook. As part of the study an assessment was undertaken by members of GA, CSIRO, ASA, and UNSW during a concurrent design facility session.

The risks were classified on a likelihood and severity of impact scale to classify them into high, medium, and low magnitude risks as per the schema shown in Table 17.

Table 17 Risk magnitude classification scheme

Risk magnitude		Severity of impact				
		Negligible	Significant	Major	Critical	Catastrophic
Likelihood	Maximum	Low	Medium	High	High	High
	High	Low	Medium	Medium	High	High
	Medium	Low	Low	Medium	High	High
	Low	Low	Low	Medium	Medium	High
	Minimum	Low	Low	Low	Medium	High

In total, 54 risks have been identified, of which 13 were classified into the high-risk category, 32 into one of the medium and 10 into the low-risk. All risks with high magnitude are listed in Table 18. For these risks, mitigation actions have been identified and are listed in the table. Each risk is designated as only applicable to the Australian implementation, the overseas or both (“All”) procurement pathways.

The highest risk item is cost and schedule expansion due to scope creep, resulting in an unaffordable mission.

All findings in this report are based on the defined set of mission requirements and objectives and any modification of them would have a direct impact on the mission cost, schedule, and risk profile. The mission owner will need to control scope throughout the design process to help maintain the accuracy of the estimates made in this study.

The Australian missions would also strongly benefit from opportunities of partnerships with and mentorship by international partners, which can help mitigate the risks.

Table 18 High risks and identified mitigation actions

Risk item	Applicable to	Likelihood	Impact	Mitigation actions
Mission becomes unaffordable and is cancelled	All	**Maximum**	**Catastrophic**	Agreed process and timeframes for freezing of scope.

Risk item	Applicable to	Likelihood	Impact	Mitigation actions
Schedule slippage and reduced ability to effectively manage the capability development process.	Overseas	**Maximum**	Critical	Early identification and agreement on sharing of project management, systems engineering, design, construction, integration, operations, sustainment, and disposal lessons learned. Early engagement of legal advisors. Ensure time required to establish sharing frameworks is reflected in schedule.
Australian industry does not benefit from the mission	Overseas	**Maximum**	Major	Precise articulation of AUS industry content requirements in procurement criteria.
Inability to transfer vital technical information between US and Australian stakeholders.	All	High	Critical	Ensure suitable agreements and mechanisms are part of the mission objectives. Early identification and validation of all transfer requirements by both US and AUS stakeholders. Early engagement of legal advisors.
Low stakeholder confidence in ability of Australian industry to deliver mission outcomes	AUS	High	Critical	Clear articulation of stakeholder Needs Goals and Objectives. Frequent working groups with all stakeholders, including Australian industry and experienced international partners. Development and demonstration of capability through use of 2 pathfinder missions.
Inability to overlap observations with CLARREO due launch delays.	AUS	Maximum	Major	Prime to engage closely with the LSP to be informed of on any schedule slips. Preference to be the Prime payload on launcher to avoid external schedule slips.

Risk item	Applicable to	Likelihood	Impact	Mitigation actions
Stakeholder management and supply chain quality assurance	AUS	Medium	Critical	Those aspects to be reviewed to clear the gate at every Mission milestone review. Expert review committee comprised of industry experts, Agency, GA, CSIRO etc.
Spacecraft cannot achieve and maintain orbits needed to make observations	All	Medium	Critical	Ensure propulsion systems reliability and capacity: validated orbit keeping requirements; heritage components; redundancy; testing, and effective propulsion management during mission operations.
Spacecraft power system fails before design lifetime	All	Medium	Critical	Ensure power systems reliability: heritage components; redundancy; testing, and effective power management during mission operations.
Failure to meet COPUOS deorbit obligations	All	Medium	Critical	Employ redundant active subsystems to facilitate deorbit; mission operations policy to accelerate deorbit schedule if subsystems degrade; use of high-drag spacecraft design to promote passive deorbit inside 25 years.
Launch failure	All	**Minimum**	**Catastrophic**	Use well established LSPs with a solid track record. If multiple spacecraft, split launches between launch vehicles and LSPs.
Space craft is dead-on-arrival	All	**Minimum**	**Catastrophic**	Rigorous, appropriate, and relevant test campaign with focus on LEOP. Pathfinder timeline with suitable time to apply lessons-learnt to FOC
Collision with another A-train spacecraft	All	**Minimum**	**Catastrophic**	Separation of orbits. Redundant, heritage propulsion. Well defined mission operations policy and process with access to appropriate space situational awareness information. Manoeuvre coordination with reference missions.

Medium risks are listed in Table 19. Due to the limited duration of this Pre-phase A study, a mitigation strategy has only been identified for some of the risks. As this work is not complete, it is not described in detail.

In general, the medium risks are more of a technical nature than the high risks and many of the mitigation strategies identified for the high risks will have beneficial mitigative effects on the lower magnitude risks. Cyber-related risks have been assessed as medium magnitude with a cyber-attack on the space segment having mission-critical impact, but with existing best-practices of encryption, authentication and authorization being of minimum likelihood.

Table 19 Medium risks identified

Risk item	Type	Likelihood	Impact	Comment
Low TRL of AUS instrument	Programmatic	High	Major	Pathfinder procurement options
On-board calibration system not able to demonstrate performance stability over lifetime (low TRL)	Technical	High	Major	Technology de-risk opportunity
High data rate downlink radio (low TRL)	Programmatic	High	Major	mitigation actions identified
Radiometric accuracy below spec	Technical	High	Major	Technology de-risk opportunity
Project over budget	Programmatic	High	Major	mitigation actions identified
Knowledge gap in building operational Avionics/Resilient Systems	Programmatic	High	Major	AUS-made only, mitigation actions identified
Skills retention throughout pathfinder missions	Programmatic	High	Major	
Ground station tasking conflict due to A-Train orbit	Technical	High	Significant	
Small pool of experienced personnel in Australia making system reviews less beneficial	Programmatic	High	Significant	
ITAR if using Rad Hard / JAN-TX parts from US Vendors	Programmatic	High	Significant	
Space segment not ready for launch on schedule	Programmatic	High	Significant	
Spec does not demonstrate transfer cross-calibration	Technical	Medium	Major	
Launch delay due to launch provider	Programmatic	Medium	Major	Overseas only
Pathfinder failure impacting FOC mission	Programmatic	Medium	Major	
Environmental AIT facility readiness/capacity	Programmatic	Medium	Major	AUS-made only

Risk item	Type	Likelihood	Impact	Comment
Procurement flexibility to account for on-going tech developments over programme	Programmatic	Medium	Major	
Little heritage in 30-50kg S/C size	Programmatic	Medium	Major	AUS-made only
Unable to achieve precise orbital injection/required orbit	Technical	Low	Critical	
Failure of the on-board anomaly handling software	Technical	Low	Critical	mitigation actions identified
Specifying and developing a representative Pathfinder within Budget/Schedule	Programmatic	Low	Critical	
Failure of onboard calibration system (HSI aperture blocked)	Technical	Low	Critical	
Use of component which removes partner involvement in mission	Political	**Minimum**	Critical	
Optics system contamination in-orbit	Technical	**Minimum**	Critical	
Cyber-attack on spacecraft	Programmatic	**Minimum**	Critical	mitigation actions identified
Spec does not demonstrate independent cross-cal	Technical	Low	Major	
General failure of onboard calibration system	Technical	Low	Major	
Spacecraft put in an unsafe state due to errors in automated scheduling software	Technical	Low	Major	mitigation actions identified
Partial or full ADCS failure degrades pointing performance for imaging and GS communications	Technical	Low	Major	mitigation actions identified
Use of component which removes partner ground station opportunities	Political	Low	Major	
Instrument design inherently unable to meet radiometric accuracy requirement	Technical	Low	Major	
HSI imager not meeting operational lifetime	Technical	Low	Major	
Cyber-attack on ground segment (GS and processing chain)	Programmatic	Low	Major	mitigation actions identified

Table 20 lists risk items of low magnitude as identified in the study. Again, many of them will benefit from mitigation actions identified for high-risk items.

Table 20 Low risk items identified

Risk item	Type	Likelihood	Impact	Comment
Lack of suitable AIT/optical integration facilities on-shore	Programmatic	Medium	Significant	
In-orbit commissioning phase takes longer than expected/scheduled due to unplanned issues.	Programmatic	Medium	Significant	
Incompatibility when interfacing L0 processor to L1/schedule risk in building an L0 processor in Australia	Programmatic	Medium	Significant	
Implementation of on-board data management	Technical	Medium	Significant	
Blackbox subsystems with inadequate support	Technical	Medium	Significant	Overseas only
Propulsion system does not meet specifications	Technical	Medium	Significant	AUS-made only
Delays in developing L2/L3 processing system	Programmatic	Low	Significant	
Ability to meet and prove requested operational on-orbit lifetime	Technical	Low	Significant	
Space weather event	Technical	**Minimum**	Major	
Unchartered Regulatory Regime (e.g. insurance)	Programmatic	**Minimum**	Major	

11.2 Mission operations

11.2.1 Concept of operations

The SCR mission Concept of Operations (ConOps) relies on two operational modes:

- The default mode is to perform imaging during predefined intervals of coincident observations.
- A secondary mode consists of the continuous imaging of all land cover.

In the default mode, the opportunities for coincident observations are computed on ground based on the ephemerides of all cooperative missions. The results of this computation are then used to define the satellite's imaging schedule. To a first order, this operational mode would fulfill all immediate needs for image acquisition while keeping the data volume to downlink to ground to a minimum.

The second mode would allow storage of image data in a ground archive for future use. This can serve use cases that are currently not identified but may become of interest in the future. Since this mode leads to a significant increase in the payload data budget, it shall only be implemented to the extent that it does not drive the system design.

With either of the two operational modes it shall be possible to perform imaging while downlinking payload data to a ground station. This would define a dedicated spacecraft mode with potentially challenging implications for the power budget, on-board payload data handling and antenna design.

Instrument calibration would be performed on a regular basis. This may come in several forms: Vicarious, lunar, solar or on-board calibration. The on-board calibration subsystem could be used before each imaging session. Further details on the calibration approach can be found in section 11.3.2.

The implementation of the SCR ground segment would leverage the expertise and capabilities of the Australian National Ground Segment Technical Team (ANGSTT). This ensures application of best practices in line with other national space programs and avoids unnecessary cost.

All communications between space and ground segment would employ encryption, authentication and authorisation following best practices from the Australian Signals Directorate (ASD) Information Security Manual and others if applicable.

Further details on the data processing pipeline including how external stakeholders would be able to interface with the different subsystems is provided in section 11.5.4.

To maximise the public impact of the SCR mission, non-sensitive details of the mission telemetry would be made available to relevant space educational institutions after GA training. These include, but are not limited to the Agency's Australian Space Discovery Centre (ASDC), Victorian Space Science Education Centre (VSSEC), Mount Stromlo Space and STEM Education centre and others.

11.2.2 Mission operations centre

The SCR MOC has been introduced in section 0. This section provides further details.

Specifically, required infrastructure for the MOC would include:

- software tools to propagate and visualise spacecraft orbits and ground station passes;
- software tools to encode telecommands and decode telemetry into human-readable data safely and automatically;
- software tools to optimise spacecraft tasking and automatically output the required telecommands;
- software tools that allow telecommands to be generated, reviewed, approved, and sent to a ground station for transmission to an SCR series spacecraft;

- a filterable cloud-based database of communications between the ground stations and SCR series spacecraft. This database includes all commands that are uplinked and all responses that are received, including housekeep telemetry, configuration data, payload data, and spacecraft log files;
- methods to set warning limits for telemetry fields so that operators can be immediately notified of non-nominal spacecraft health;
- software tools for visualisation and trending of spacecraft telemetry;
- methods to export and share telemetry and payload data in accessible formats.

Significant up-front development is required for the MOC prior to the first SCR series pathfinder, after which only updates and maintenance are required for continued reliability and compatibility with later missions. An initial investment in operations development is expected to pay off with reduced operational costs after launch and greater mission outcomes. The MOC would be used for on-orbit operations, operator training, and as discussed in section 0, system level testing before and after launch.

Table 21 lists the elements of the MOC and their estimated costs. The assumptions made in this cost estimate are:

- the software infrastructure would be developed from the ground up, or substantial modification would need to be made to an existing infrastructure to support the mission,
- a moderate level of automation would be built into the operations software, as described in section 10.1.7.1,
- operations staffing is restricted to business hours, with the exception of the launch and early orbit period (LEOP),
- staffing costs are AUD 200K per person per annum, including overheads.

Table 21 Breakdown of MOC cost estimate

Item	Staffing (person months)	Cost (AUD M)
TT&C handling	42	0.7
Automated spacecraft tasking software	96	1.6
Operator training	33	0.6
Mission operations	72	1.2
Total	**243**	**4.1**

11.2.3 Sustainability of operations concept

To reduce the accumulation of space debris, Earth-orbiting missions must be designed to adhere to disposal policies defined at a national level or by the customer. Section 4.6 of NASA Standard 8719.14, Process for Limiting Orbital Debris[81] states that a spacecraft with a perigee altitude below 2000 km shall disposed of by leaving it in an orbit in which natural forces would lead to atmospheric re-entry within 25 years after the completion of the mission, or manoeuvre the spacecraft into a controlled deorbit trajectory as soon as practical after completion of the mission. Typically, spacecraft in orbits above 600 km altitude are unable to re-enter naturally within 25 years, and require an end-

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[81] NASA, 2019, Process for Limiting Orbital Debris, NASA-STD-8719.14B, https://standards.nasa.gov/standard/osma/nasa-std-871914.

of-mission manoeuvre for controlled re-entry or to reduce the orbital altitude to enable re-entry within 25 years.

A deorbit manoeuvre is only possible if the end-of-mission is planned, that is, the mission objectives have been completed to the extent possible and a decision is made to proceed to the disposal phase of the mission while the spacecraft bus is still functional. If a failure occurs to a critical platform component during the mission, it may not be possible to command the deorbit manoeuvre and the spacecraft would not re-enter within the required 25 years. For a planned deorbit manoeuvre, NASA recommends that the probability of post-mission disposal should be no less than 0.9, with a goal of 0.99 or better[82]. Any SCR series spacecraft that are launched to trail Landsat or Sentinel 2 satellites must be designed and tested for high reliability over the mission lifetime to mitigate the risk of creating space debris in a highly populated 700-800 km altitude polar orbit. We recommend that any pathfinder missions target an orbit of less than 600 km altitude.

All planned, confirmed, and cancelled manoeuvres for orbit insertion, station keeping, would be reported to the 18th Space Control Squadron (18 SPCS) as per 18 SPCS's Spaceflight Safety Handbook for Satellite Operators[83]. Additionally, regular ephemeris data from the on-board GPS would be supplied to 18 SPCS to improve the accuracy of the catalogue entries and conjunction assessments for the SCR series spacecraft.

11.2.4 Orbit mechanics and propulsion requirements

As discussed in section 9.5, the SCR orbit has not been completely defined at this stage. Nonetheless, this chapter provides some supporting analyses to facilitate orbit selection and inform the design of a propulsion subsystem for the SCR mission.

The need for on-board propulsion for the SCR mission may be driven by two operational needs:

- Compliance with space debris mitigation standards, notably the need to vacate the LEO protected region within 25 years after the end of the nominal mission.
- Station acquisition or station keeping needs in a formation flying scenario.

The 25-year goal can be achieved by leveraging atmospheric drag of a spacecraft. For typical micro- or nano-satellites this is possible at orbital altitudes below ~600km - ~650km. At higher altitude, the atmospheric density would not be able to provide sufficient drag to achieve the desired re-entry timeframe.

Station acquisition may become important in the case that the SCR satellite is launched as a secondary payload and the primary payload on that launcher is targeting an orbit which is not suitable for SCR. It may be required to manoeuvre the SCR spacecraft to the final orbit on its own accord.

Station keeping may be required if flying in formation with another satellite that has different aerodynamic properties so that a natural drift would accumulate over time. In this case, propulsion would be needed in regular intervals to keep the relative orbital position.

The total impulse required for deorbit or station acquisition is expected to be much larger than any station keeping needs. This is because the orbit may need to be changed significantly whereas in a station keeping scenario only small adjustments are required. Figure 8 maps the required delta-V for a Hohmann transfer between an initial orbit of given altitude and a given altitude change. It should be noted that utilising Hohmann manoeuvres in the LEO region yields an error of <5% even if

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[82] US Government, 2019, Orbital Debris Mitigation Standard Practices, https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf

[83] 18th Space Control Squadron, 2020, Spaceflight Safety Handbook for Satellite Operators, Version 1.5, https://www.space-track.org/documents/Spaceflight_Safety_Handbook_for_Operators.pdf.

compared to realistic continuous low-thrust manoeuvres. The plot shows that to move a satellite from a 700km orbit to a 500km passive re-entry orbit would require ~100m/s delta-V.

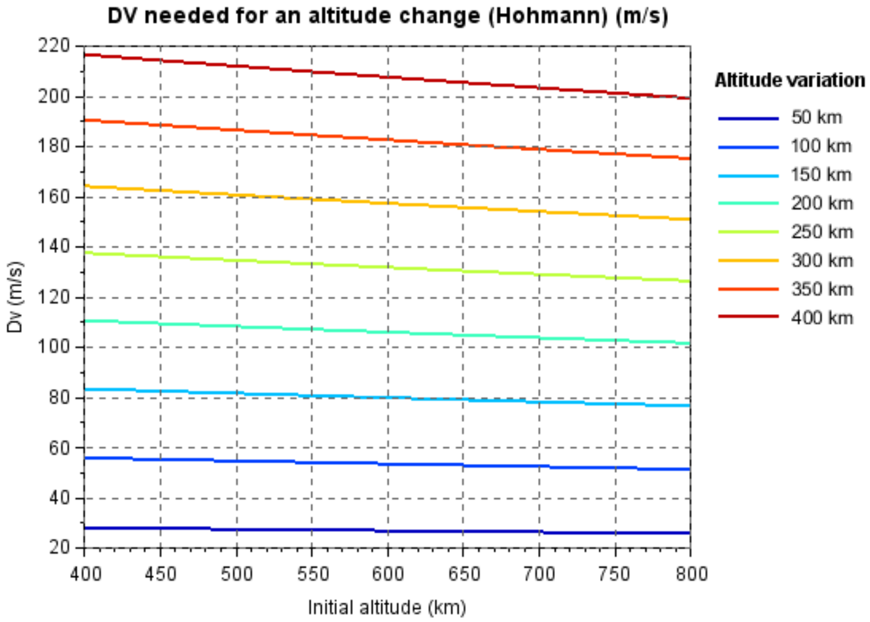

Figure 8 Circular-to-circular orbit manoeuvre delta-V requirement as function of initial orbit altitude and change in altitude

The required mission delta-V in combination with the selected propulsion technology would determine the mass fraction of the propellant in relation to the satellite's dry mass. This relationship is plotted exemplarily for a 50kg spacecraft in Figure 9. The range of specific impulse (Isp) values included in the graph represents the range as achievable by cold gas (<100s) over chemical (150s – 350s) to electrical (>1000s) propulsion subsystems. To continue the above example: For a 100m/s mission, a cold gas system would require ~10% (=5kg) of propellant, while an electrical system would need <1% (=0.5kg).

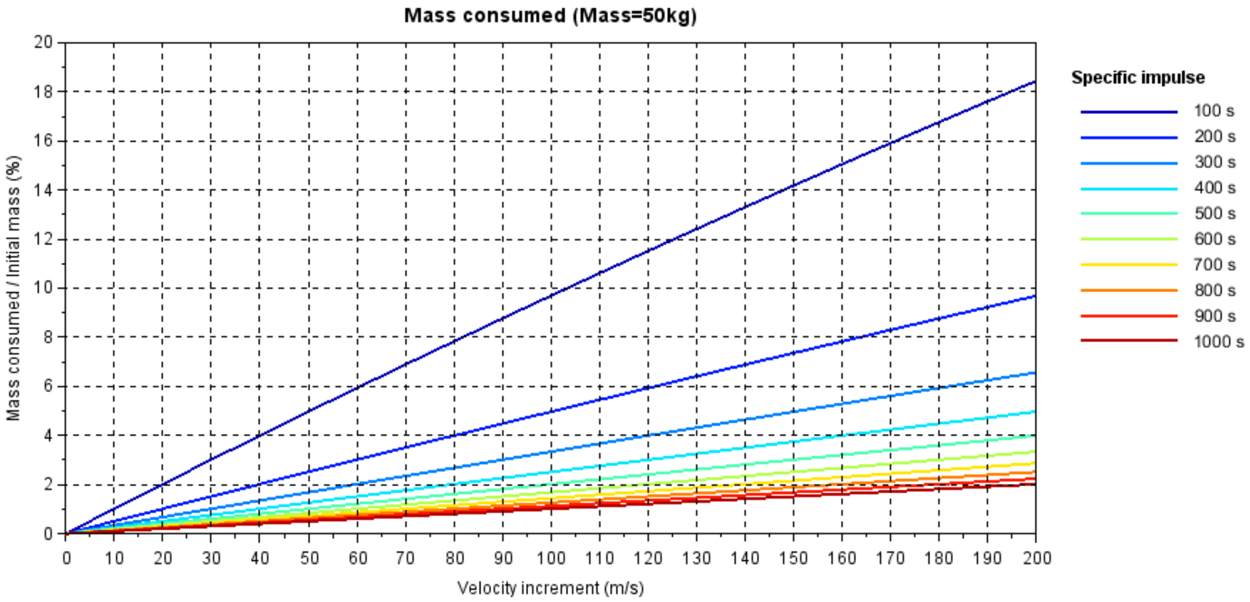

Figure 9 Propellant mass fraction depending on delta-V and specific impulse of propulsion subsystem

While fuel efficiency increases for higher Isp propulsion subsystems, thrust decreases. Typical thrust levels for Hall-effect thrusters (Isp ~1000s) are in the order of a few mN. This leads to the need of a substantial period for thrusting to achieve a certain orbit change. Continuing the above example, performing a manoeuvre of 100m/s using a thruster with 1.8mN of thrust requires ~3E6s or 35 days of continuous thrusting as plotted in Figure 10. This does not consider the fact that typically there is not enough electrical power available during orbital eclipse, which would naturally extend the required period by a factor of ~1.5.

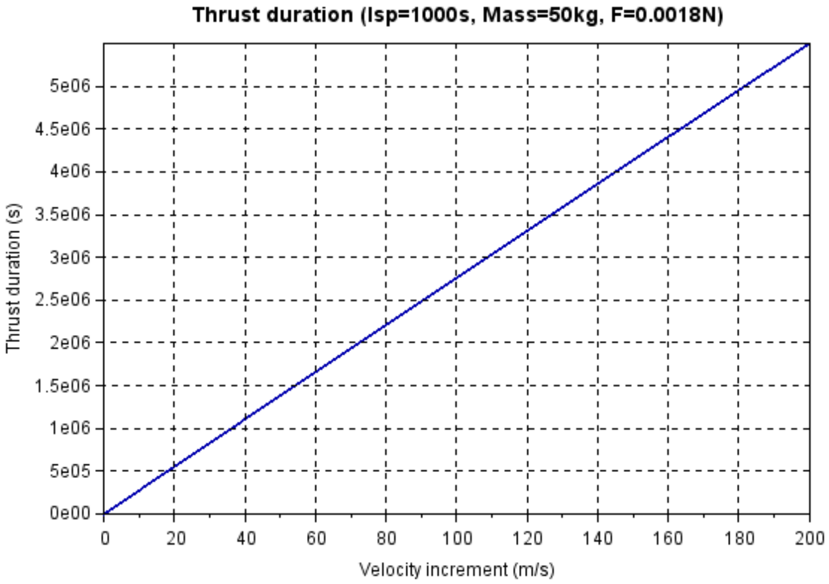

Figure 10 Thrust duration as function of delta-V for a 1.8mN thruster on a 50kg satellite

The selected propulsion technology would need to balance all presented conflicting effects to best meet the mission goals.

11.2.5 Orbit analysis

11.2.5.1 Target Orbits

The primary target orbits for this mission are Landsat-8, Sentinel-2A, and Sentinel-2B. Landsat-8 is in a repeating groundtrack, sun-synchronous orbit at approximately 700km altitude. Sentinel-2A and Sentinel-2B are in repeating groundtrack, sun-synchronous orbit at approximately 800 km altitude, spaced 180 degrees apart within their orbit. All three spacecraft orbits are oriented such that the descending node occurs on the Earth's dayside, which will be used to evaluate opportunities for coincident data collection. A summary of the orbit parameters is included in Table 22, using data retrieved from the public Two-Line Element (TLE) catalog and mission websites.

Table 22 Target Orbit Parameters[84]

Mission	NORAD	Alt (km)	Inc (deg)	LTDN	N_{To} (revs)	C_{To} (days)	Swath (km)
Landsat-8	39084	698.2	98.2	10:11	233	16	185
Sentinel-2A Sentinel-2B	40697 42063	792.1	98.5	10:29	143	10	290

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[84] Altitude, Inclination, and LTDN obtained from TLE data retrieved from www.space-track.org May 2, 2021. Landsat-8 recurrence and swath parameters retrieved from https://www.usgs.gov/core-science-systems/nli/landsat/landsat-8?qt-science_support_page_related_con=0#qt-science_support_page_related_con and https://landsat.gsfc.nasa.gov/about/worldwide-reference-system. Sentinel-2 recurrence and swath parameters retrieved from https://sentinel.esa.int/web/sentinel/missions/sentinel-2/satellite-description and https://sentinel.esa.int/web/sentinel/missions/sentinel-2/satellite-description/orbit.

11.2.5.2 Repeating Groundtrack and Sun-Synchronous Orbit

Repeating groundtrack, or recurrent, orbits are defined such that an integer number of orbit revolutions occur during an integer number of Earth rotations (sidereal days). Adopting the nomenclature of Capderou[85], these quantities are referred to as N_{To} and C_{To}, respectively. These terms define the nodal period, the time between equator crossings, which can be used to iteratively solve for the orbit semi-major axis. This in turn can be used to compute the inclination required to achieve sun-synchronous orbit, while the Right Ascension of Ascending Node (RAAN) is used to achieve the desired Local Time of Ascending/Descending Node (LTAN/LTDN). The nodal period is given by:

$$T_d = \frac{C_{To}}{N_{To}} D^* \qquad D^* = 86164.1\,\text{sec} = 1\text{ sideral day}$$

This is used to compute an initial estimate for the mean motion, or equivalently, semi-major axis:

$$n_0 = \frac{2\pi}{T_d} \qquad a_0 = \left(\frac{\mu}{n_0^2}\right)^{1/3}$$

As a result of the J_2 perturbation, orbit elements such as RAAN and argument of periapsis incur secular changes, which in turn affects the nodal period. The following set of equations is iteratively solved until converging on the final mean motion, which gives the desired semi-major axis of the recurrent orbit[86]:

$$\dot{\Omega} = -\frac{3}{2}\left(\frac{360}{2\pi}\right) J_2 \mu^{1/2} R_E^2 a^{-7/2} \cos i \,(1 - e^2)^{-2}$$

$$\dot{\omega} = \frac{3}{4}\left(\frac{360}{2\pi}\right) J_2 \mu^{1/2} R_E^2 a^{-7/2} (5\,(\cos i)^2 - 1)(1 - e^2)^{-2}$$

$$\dot{M} = \frac{3}{4}\left(\frac{360}{2\pi}\right) J_2 \mu^{1/2} R_E^2 a^{-7/2} (3\,(\cos i)^2 - 1)(1 - e^2)^{-3/2}$$

$$n = \left(\frac{Nto}{Cto}\right)\left(360 - \dot{\Omega}\right) - (\dot{\omega} + \dot{M})$$

where all the angular rates are expressed in degrees per sidereal day.

The previous equations are also dependent on the orbit inclination and eccentricity. For the orbits considered in this report, an arbitrarily small value of eccentricity is selected to model a near-circular orbit, and inclination is computed simultaneously with semi-major axis to meet the sun-synchronous orbit condition, namely that $\dot{\Omega} = n_E$, the mean motion of the Earth's orbit about the sun.

Recurrent orbits are often defined with the set of three integers $[\nu_o, D_{To}, C_{To}]$ where ν_o is the integer number of revolutions per day, C_{To} is the integer number of days in the repeat cycle, and D_{To} is the remainder such that the integer number of revolutions in the repeat cycle N_{To} is given by:

$$N_{To} = \nu_o C_{To} + D_{To}$$

The final quantity of interest for this analysis is the grid interval at the equator, δ, which defines the angular distance between adjacent groundtracks in the full recurrent orbit cycle:

$$\delta = \frac{360°}{N_{To}}$$

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[85] Capderou, M., "Handbook of Satellite Orbits," Springer International Publishing, 2014

[86] Wertz, J.R., Everett, D.F., and Puschell, J.J., "Space Mission Engineering: The New SMAD," Microcosm Press, 2011

11.2.5.3 Swath Width and Field of View

Referring to Figure 11, the instrument swath is related to the field of view (FOV) and orbit altitude as shown in Figure 12 such that either quantity can be computed from the other, for a given orbit. Assuming a spherical Earth, the relationship between the half-swath angle α and half-FOV angle f is given by:

$$\frac{\sin f}{R_E} = \frac{\sin \zeta}{a} \qquad \alpha = \zeta - f$$

while the swath width, s, and FOV are defined by:

$$s = 2\alpha R_E \qquad \text{FOV} = 2f$$

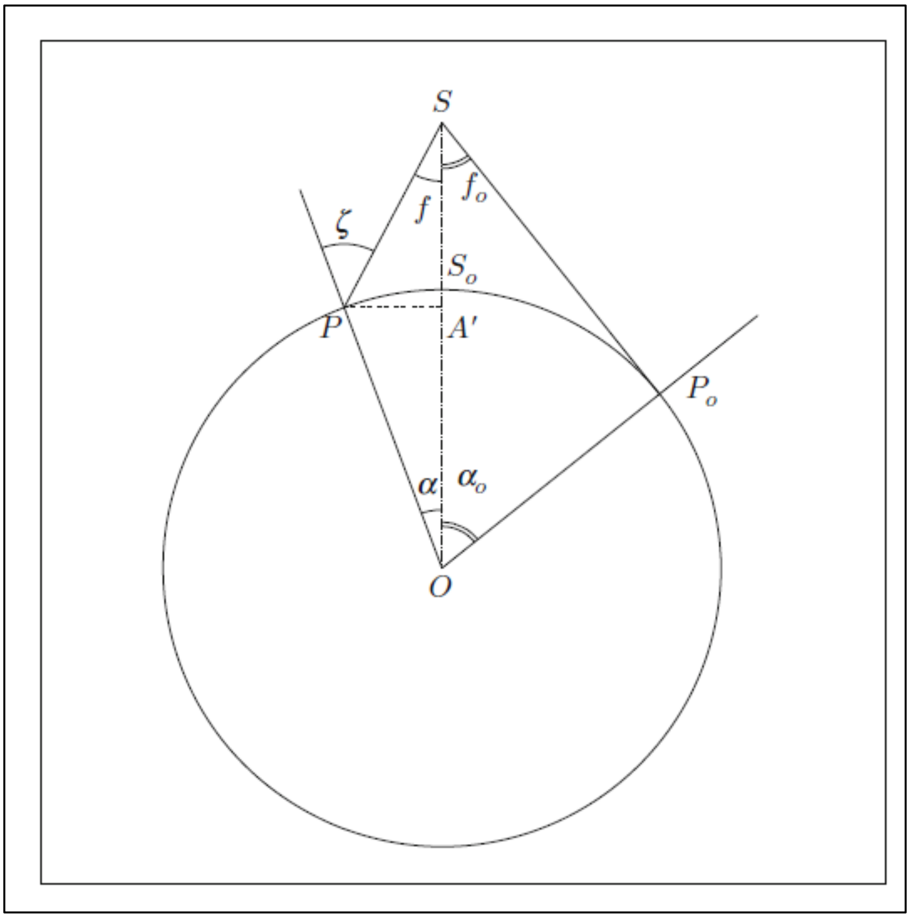

Figure 11 Illustration of relationship between half-swath angle α and half-FOV angle f [Capderou, 2014 Ch. 12]

Given the swath and recurrence parameters for the missions, it is possible to compute the grid interval δ between adjacent groundtracks. If the angle $\delta < 2\alpha$, it ensures the full coverage pattern will not have any gaps, a condition that is met for both the Landsat-8 and Sentinel-2 orbits, and a criterion that will be evaluated for candidate orbits.

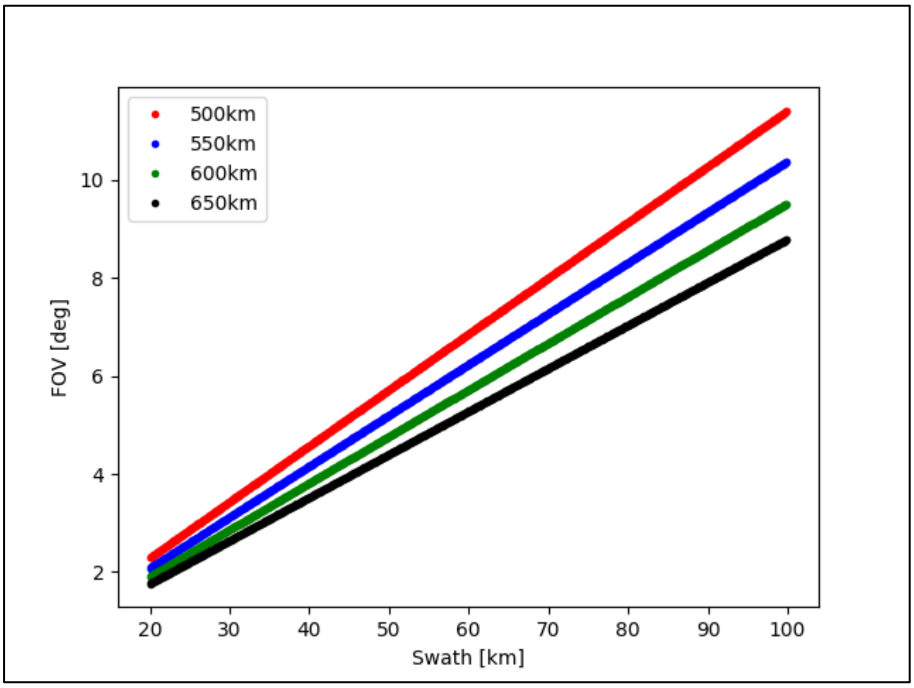

Figure 12 Field of View vs Swath Width at Different Altitudes

11.2.5.4 Coverage and Coincidence Analysis – Target Orbits

The Landsat-8 coverage pattern is defined using the Worldwide Reference System 2 (WRS2), a set of numbered paths and rows corresponding to longitude and latitude (Figure 13)[87]. Paths are numbered 1-233 from East to West beginning at 64.60º W at the Equator. Rows are numbered 1-122 from North to South beginning at 80.78° N and ending at 81.85º S. This means there are a total of $233 \times 122 =$ 28,426 bins on the dayside of the Earth, of which 6954 have center locations over land.

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[87] https://landsat.gsfc.nasa.gov/about/worldwide-reference-system

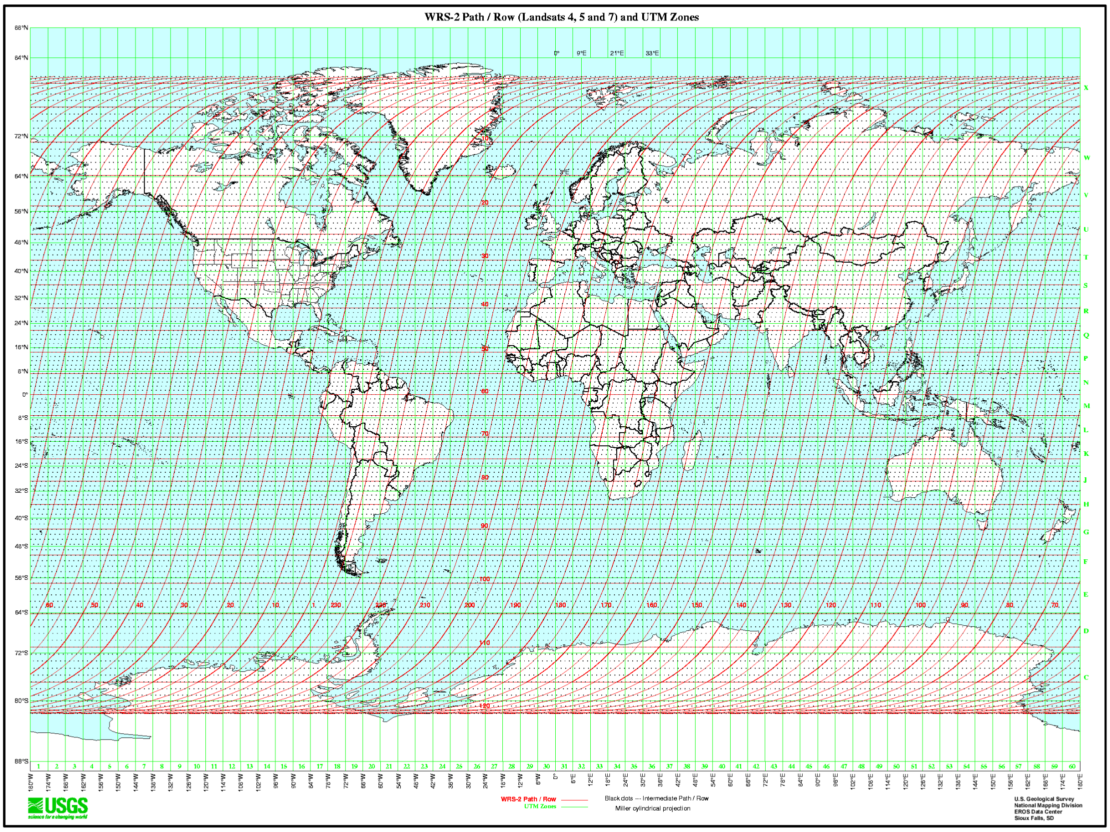

Figure 13 Worldwide Reference System 2

The coincidence conditions for Landsat-8 and Sentinel-2 are evaluated by retrieving and propagating orbits from the public TLE catalog for a time period of one year. In order to account for periodic orbit maintenance maneuvers, historical TLE data are used, as opposed to propagating a current set of TLEs one year into the future. The time period used is June 1, 2020, through May 31, 2021. TLE data are retrieved from www.space-track.org for the year and are typically updated once or twice daily. Each TLE is used to propagate the orbit using SGP4 until the epoch time of the subsequent TLE, using a ten-second step size. The output of this process is a time series of Cartesian state vectors in the True Equator Mean Equinox (TEME) coordinate frame. These are converted to the Geocentric Celestial Reference Frame (GCRF) and then the International Terrestrial Reference Frame (ITRF) and finally geodetic latitude and longitude.

The cross-track swath coverage is computed assuming nadir-pointing, and comparisons are done between the Landsat-8 and Sentinel-2 data. Overlaps are counted as occurring within the WRS2 bin with center location closest to the center of the overlap, and if multiple overlaps are computed in the same bin during the same pass, the one with the higher swath overlap is retained. Overlaps are only counted if the passes occur within 30 minutes of one another. Landsat-8 observations are restricted to the range [-81.85°, 80.78°] latitude, coinciding with the boundaries of the WRS2 grid. Sentinel-2 observations are restricted to the range [-56°, 83°], per the description on the mission website.[88] The website further notes that Sentinel-2 observations are made over land and coastal areas, and therefore results are presented considering WRS2 bins on land separately and in addition to the overall total.

The results are summarized in Table 23. The first column presents the total number of WRS2 bins with overlapping swath between Landsat-8 and either Sentinel-2A or Sentinel-2B over the course of the year. The second column identifies the number of unique WRS2 bins with coincident data collects, out of the total 28,426 on Earth dayside. The third column presents the average overlap in

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[88] https://sentinel.esa.int/web/sentinel/missions/sentinel-2/observation-scenario

kilometers for the WRS2 bins with nonzero overlap. Columns 4-6 present a subset of the same data selected to include only WRS2 bins with center locations on land, of which there are 6954.

Table 23 Landsat-8/Sentinel-2 Coincidence Data

Overall			Over Land		
Total WRS2 Bins	**Unique WRS2 Bins**	**Average Overlap (km)**	**Total WRS2 Bins**	**Unique WRS2 Bins**	**Average Overlap (km)**
351403	23067/28426	115.94	105588	6954/6954	118.38

Results are further detailed in Figure 14, which provides a heatmap for the number of overlapping passes for each WRS2 bin mapped to the latitude and longitude at the center of each bin and overlaid with land boundaries on the world map.

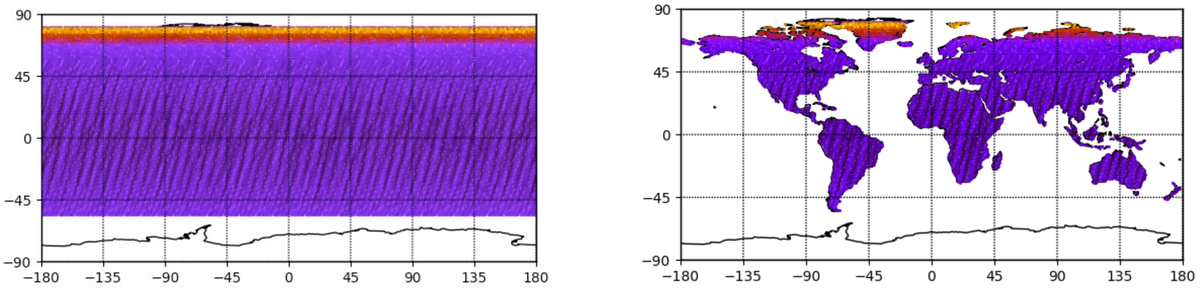

Figure 14 WRS2 Overlap Counts on World Map for Landsat-8 and Sentinel-2

The left subfigure illustrates that within the operational latitudes [-56°, 80.78°], complete coverage is attained with no gaps, while the right subfigure shows that within these constraints, all WRS2 bins on land are covered. The highest number of overlaps, up to 76 per bin (75 per bin on land) are achieved at high latitude, as expected for the near-polar orbits occupied by the spacecraft.

Figure 15 provides a view of coincidence over time, with the number of paths with at least one overlapping WRS2 bin plotted as a function of the day of year (DOY). Because the year covers from June 1, 2020 (DOY 153) to May 31, 2021 (DOY 151), there is a gap of one day, and data to the right covers 2020 while data to the left covers 2021. In addition to the comprehensive geographic coverage of coincident data collects in Figure 14, this plot shows that there are consistent coincident data collection opportunities throughout the year.

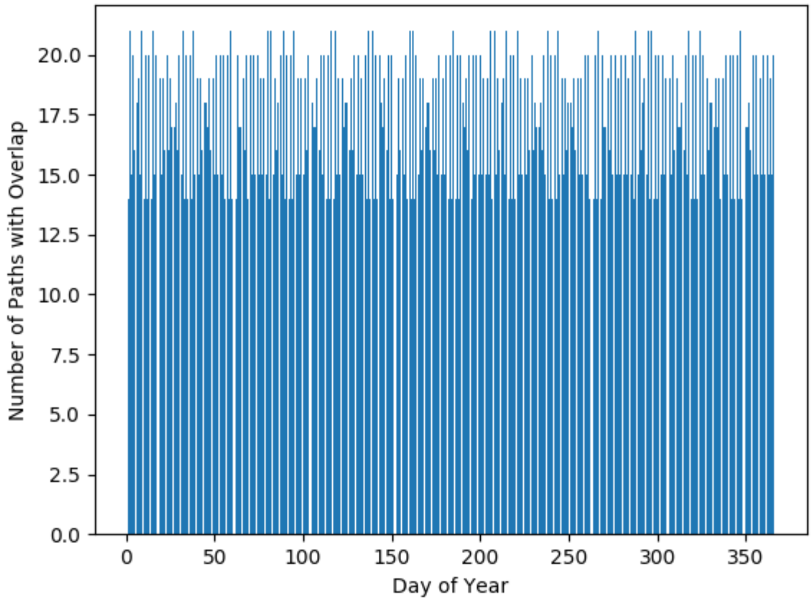

Figure 15 Number of Paths with Overlap for Landsat-8 and Sentinel-2

Figure 16 and Figure 17 present the number of WRS2 bins with overlap and the amount of overlap over the course of the year, respectively. This further illustrates that many high-quality coincident data collects can be obtained throughout the year.

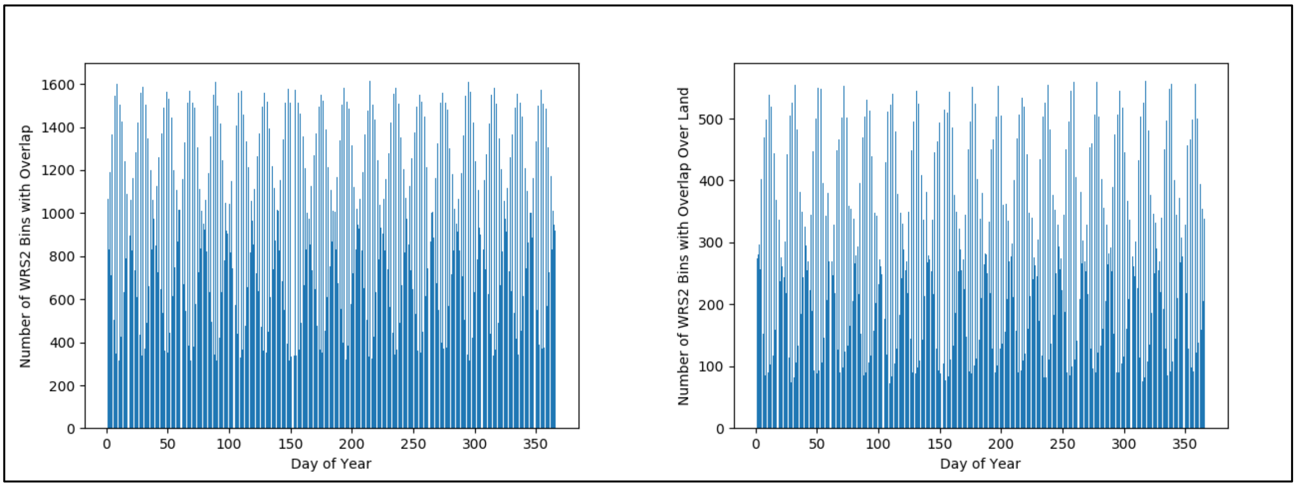

Figure 16 Number of WRS2 Bins with Overlap for Landsat-8 and Sentinel-2

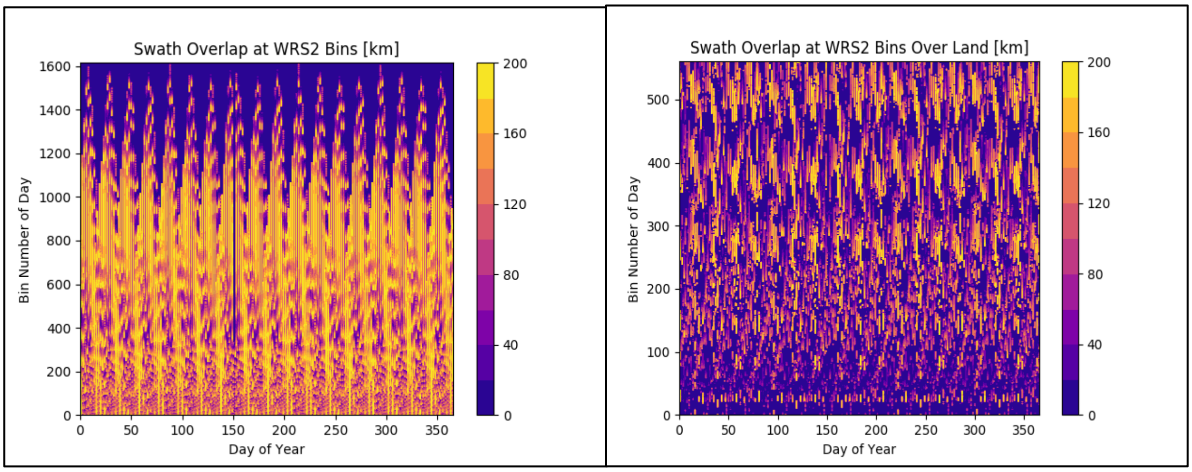

Figure 17 Swath Overlap of WRS2 Bins for Landsat-8 and Sentinel-2

11.2.5.5 Candidate Orbit Selection

The results presented for Landsat-8 and Sentinel-2 coincident coverage represent a baseline, or best-case scenario, for the possibility of triple coincident data collects with the new candidate orbit. Selection of an orbit with the same parameters as Landsat-8, but trailing slightly behind, should achieve similar numbers and quality of coincident data collects, limited by the swath width of the new instrument. The remainder of this report examines the performance of 32 other candidate orbits, selected in the altitude range from 400-650 km.

The set of candidate orbits are generated for cases of recurrent sun-synchronous orbits, with recurrence triples defined by $[v_o, D_{To}, C_{To}]$. Landsat-8 and Sentinel-2 repeat on cycles of 16 and 10 days, respectively, which has the lowest common multiple of 80 days. The first set of candidates are chosen with repeat cycles of 16, 20, and 40 days such that they share this common multiple. Candidates are also evaluated for the integer number of days E_{To} before the first adjacent groundtrack (an angular distance δ from the original groundtrack at the Equator). It is best practice to avoid selecting orbits with E_{To} of one day to achieve more coverage through the base interval during the repeat cycle.

Because recurrent orbits repeat their groundtrack at regular intervals, in order to achieve global coverage with no gaps, it is necessary to choose an appropriate FOV (equivalently swath) to ensure the condition $\delta < 2\alpha$ is met. For each of the recurrent orbit candidates, a minimum swath width in kilometers and equivalent minimum FOV in degrees have been computed to achieve full coverage with no gaps. A second set of recurrent orbit candidates are considered with longer repeat cycles of 48, 56, and 60 days, which yield options with smaller grid interval δ and therefore smaller required values of swath and FOV to achieve full global coverage.

The full set of candidate orbits and their recurrence parameters are included in Table 24, along with Landsat-8 and Sentinel-2 for reference. Note that the altitude given for Landsat-8 and Sentinel-2 are for the theoretical recurrent orbit and differ slightly from the observed values retrieved from the TLEs. Comparison between Table 23 and Table 24 confirms that Landsat-8 and Sentinel-2 achieve the condition for full coverage. The set of recurrent orbit candidates have been given IDs numbered in the 10000s.

Table 24 Candidate Orbit Summary

Mission	NORAD	Alt (km)	v_o (revs/day)	D_{To} (revs)	C_{To} (days)	N_{To} (revs)	E_{To} (days)	Min. Swath (km)	Min. FOV (deg)
Landsat-8	39084	699.57	15	-7	16	233	7	172.00	14.00
Sentinel-2A Sentinel-2B	40697 42063	786.13	14	3	10	143	3	280.24	20.17
Candidate	10001	503.64	15	3	16	243	5	164.92	18.58
Candidate	10002	466.05	15	5	16	245	3	163.57	19.88
Candidate	10003	515.01	15	3	20	303	7	132.26	14.62
Candidate	10004	454.88	15	7	20	307	3	130.54	16.32
Candidate	10005	425.30	15	9	20	309	9	129.69	17.33
Candidate	10006	492.31	15	9	40	609	9	65.80	7.65
Candidate	10007	477.27	15	11	40	611	11	65.59	7.86
Candidate	10008	462.32	15	13	40	613	3	65.38	8.09
Candidate	10009	432.66	15	17	40	617	7	64.95	8.58
Candidate	10010	417.95	15	19	40	619	19	64.74	8.86
Candidate	10011	403.32	16	-19	40	621	19	64.53	9.15
Candidate	10012	584.27	15	-3	40	597	13	67.13	6.57
Candidate	10013	537.91	15	3	40	603	13	66.46	7.07
Candidate	10014	507.42	15	7	40	607	17	66.02	7.44
Candidate	10015	619.55	15	-3	16	237	5	169.09	15.53
Candidate	10016	607.74	15	-3	20	297	7	134.93	12.66
Candidate	10017	631.41	15	-9	40	591	9	67.81	6.15
Candidate	10018	615.61	15	-7	40	593	17	67.58	6.28
Candidate	10019	645.98	15	-13	48	707	11	56.68	5.02
Candidate	10020	632.73	15	-11	48	709	13	56.52	5.11
Candidate	10021	606.43	15	-7	48	713	7	56.21	5.31
Candidate	10022	593.37	15	-5	48	715	19	56.05	5.41
Candidate	10023	588.72	15	-5	56	835	11	47.99	4.67
Candidate	10024	577.60	15	-3	56	837	19	47.88	4.75
Candidate	10025	645.03	15	-15	56	825	15	48.58	4.31
Candidate	10026	633.68	15	-13	56	827	13	48.46	4.38
Candidate	10027	622.37	15	-11	56	829	5	48.34	4.45
Candidate	10028	611.11	15	-9	56	831	25	48.23	4.52
Candidate	10029	628.77	15	-13	60	887	23	45.18	4.11
Candidate	10030	649.96	15	-17	60	883	7	45.39	4.00
Candidate	10031	618.24	15	-11	60	889	11	45.08	4.18
Candidate	10032	597.29	15	-7	60	893	17	44.88	4.30

Some common selections are required to perform the orbit propagation, again using SGP4. Each orbit requires a parameter related to ballistic coefficient to calculate drag forces. The SGP4 model uses a term B^* defined as:

$$B^* = \left(\frac{\rho_0}{2}\right)\left(C_D\frac{A}{m}\right)$$

where ρ_0 is a reference atmospheric density, and $\left(C_D\frac{A}{m}\right)$ is the ballistic coefficient. Assuming the candidate spacecraft is a small satellite, a value of $B^* = 0.28772 \times 10^{-4}\frac{1}{ER}$ was selected, taken from an operational 12U CubeSat on orbit at 550 km altitude.[89] All candidate orbits were initialized with a

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[89] TLE for RAAF M2 CubeSat (NORAD 47967) retrieved June 14, 2021.

small eccentricity $e = 10^{-4}$ and argument of periapsis $\omega = 0°$. Inclination is computed to meet the sun-synchronous orbit condition. RAAN is computed to achieve LTDN of 10:30 and true anomaly is computed such that the initial orbit groundtrack at the start of the simulation (June 1, 2020) follows that of Landsat-8. The orbit is propagated for one year, in ten-second increments, and groundtrack and swath coverage are computed as before. The swath is computed assuming the instrument will achieve an 80 km swath from 600 km altitude, which yields a field of view of $7.63°$. This is then used to compute swath for orbits at different altitude. Overlaps are processed as before, with the exception that only instances with overlap of the candidate orbit with Landsat-8 and one of the Sentinel-2 spacecrafts are included, dubbed triple coincident data collects. Note that a reduced field of view relative to that modeled should produce a similar pattern of results, with correspondingly fewer overlapping bins and reduced overlap swath coverage.

11.2.5.6 Candidate Orbit Results

Results for the candidate orbit triple coincidence coverage are presented in Table 25. As before, the results are summarized in terms of the number of WRS2 bins with triple coincident data collects and the average swath overlap for the year, subdivided into overall results, and those with WRS2 bins on land only. The highest value entry in each column is highlighted in yellow for emphasis in the discussion.

Table 25 Triple Coincidence Results

Object ID	Altitude (km)	C_{To} (days)	Overall			Over Land		
			Total WRS2 Bins	Unique WRS2 Bin	Average Overlap (km)	Total WRS2 Bins	Unique WRS2 Bin	Average Overlap (km)
10001	503.64	16	61198	13797/28426	45.68	17067	4408/6954	45.55
10002	466.05	16	59850	14250/28426	42.81	17990	4969/6954	42.17
10003	515.01	20	61651	14085/28426	46.20	18032	4760/6954	45.97
10004	454.88	20	59106	13764/28426	42.12	17440	4649/6954	42.05
10005	425.30	20	56987	12657/28426	39.77	17037	4322/6954	39.54
10006	492.31	40	61013	14195/28426	44.85	18221	4913/6954	44.51
10007	477.27	40	60380	13298/28426	43.71	17753	4666/6954	43.40
10008	462.32	40	60219	13746/28426	42.66	17993	4773/6954	43.01
10009	432.66	40	57806	12645/28426	40.32	17229	4289/6954	39.91
10010	417.95	40	56753	11107/28426	39.22	17307	3915/6954	39.20
10011	403.32	40	55425	12371/28426	38.08	16131	4233/6954	37.70
10012	584.27	40	61966	14600/28426	50.59	17577	4755/6954	50.27
10013	537.91	40	63017	14338/28426	48.02	18456	4902/6954	47.89
10014	507.42	40	61950	12177/28426	45.83	18281	4213/6954	45.75
10015	619.55	16	61828	14979/28426	52.29	17669	4808/6954	51.95
10016	607.74	20	61999	15762/28426	51.67	17916	5122/6954	51.67
10017	631.41	40	60501	13291/28426	52.53	17393	4477/6954	51.92
10018	615.61	40	61437	15354/28426	52.29	17704	5057/6954	52.20
10019	645.98	48	60625	15277/28426	53.23	17382	5001/6954	53.29
10020	632.73	48	60606	15957/28426	52.55	17506	5276/6954	52.55
10021	606.43	48	61956	14488/28426	51.88	18017	4802/6954	51.94
10022	593.37	48	62289	16004/28426	50.98	18199	5291/6954	50.16
10023	588.72	56	61644	12466/28426	50.94	17823	4262/6954	50.87
10024	577.60	56	62321	15658/28426	50.07	18250	4955/6954	49.90
10025	645.03	56	60833	13061/28426	53.01	17294	4268/6954	52.39
10026	633.68	56	60639	14611/28426	52.78	17616	5076/6954	53.08
10027	622.37	56	61791	14048/28426	52.68	17892	4571/6954	52.56
10028	611.11	56	62106	16159/28426	51.83	17553	5408/6954	52.63
10029	628.77	60	59970	13027/28426	51.77	17097	4293/6954	51.38
10030	649.96	60	60415	15457/28426	53.68	17583	5131/6954	53.63
10031	618.24	60	61545	15037/28426	52.36	17783	4979/6954	53.04
10032	597.29	60	62071	15115/28426	51.29	18222	5143/6954	50.83

Most of the orbits achieve similar performance in terms of coincident data collection opportunities, with about 60,000 triple collects. Figure 18 provides the heatmap view of triple collects for candidate 10028, which achieved the best geographic coverage. Most coincident data collection opportunities occur at high latitude, similar to the results captured in Figure 14. The main causes of this are the use of the high inclination sun-synchronous orbits and the choice of a 10:30 LTDN, which create candidate orbits that are very similar to those of the target spacecraft. This also means that additional criteria should be evaluated to determine the most suitable candidate orbit(s).

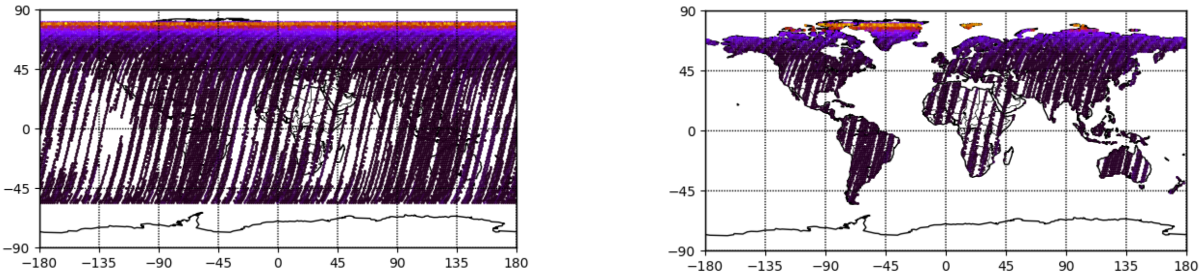

Figure 18 WRS2 Overlap Counts on World Map for Candidate 10028 Triple Collects

11.2.5.7 Summary and Recommendation

While the best-performing cases in Table 25 tend to occur for the higher altitude candidates with longer repeat cycles, it is important to consider the inaccuracies in long-term orbit prediction, and with the use of the SGP4 propagator. Overall, there does not appear to be much differentiation between the candidates considered in terms of coincident data collection. Each of the orbits produces tens of thousands of coincident data collection opportunities, with typically more than half of the WRS2 bins covered.

The following criteria for orbit selection are recommended:

1. The orbit should be sun-synchronous with LTDN similar to Landsat-8 and Sentinel-2 (e.g. 10:30). This will ensure a high number of coincident data collection opportunities, with the note that the majority will occur at high latitude and over water.
2. The orbit altitude should exclude the range 500-575 km to avoid the SpaceX Starlink constellation operating at 550 km to mitigate against possible conjunctions.
3. The orbit should be at high altitude to increase the swath achieved for given instrument field of view and reduce the effects of drag on the orbit.
4. The orbit should make use of a long repeat cycle to reduce the grid interval and enable full global coverage with a smaller swath/field of view.

A reduced list of three candidates have been chosen based on these criteria, with the orbit parameter summary and coincident data collection results summarized in Table 26 and Table 27, respectively.

Table 26 Recommended Candidate Orbit Summary

Mission	**NORAD**	**Alt (km)**	v_o (revs/ day)	D_{To} (revs)	C_{To} (days)	N_{To} (revs)	E_{To} (days)	**Min. Swath (km)**	**Min. FOV (deg)**
Candidate	10019	645.98	15	-13	48	707	11	56.68	5.02
Candidate	10028	611.11	15	-9	56	831	25	48.23	4.52
Candidate	10030	649.96	15	-17	60	883	7	45.39	4.00

In particular, of all the orbits considered, Candidate 10030 is at the highest altitude, and achieves the lowest FOV and swath requirement as a result and can lead to a less demanding and costly optical system design. But this would need to be confirmed.

Candidate 10028 has the widest geographic coverage, as determined by the number of unique WRS2 bins with triple collects.

Finally, Candidate 10019 offers a shorter 48-day repeat cycle while still requiring only a 5-degree FOV for global coverage with no gaps and producing a relatively large swath given the high altitude.

Table 27 Recommended Candidate Triple Coincidence Results

Object ID	Altitude (km)	C_{To} (days)	Overall			Over Land		
			Total WRS2 Bins	Unique WRS2 Bin	Average Overlap (km)	Total WRS2 Bins	Unique WRS2 Bin	Average Overlap (km)
10019	645.98	48	60625	15277/28426	53.23	17382	5001/6954	53.29
10028	611.11	56	62106	16159/28426	51.83	17553	5408/6954	52.63
10030	649.96	60	60415	15457/28426	53.68	17583	5131/6954	53.63

As a result of having the smallest swath and field of view requirements, Candidate 10030 is recommended as the best available option. Figure 19 and Figure 20 present the number of WRS2 bins with overlap and the amount of overlap over the course of the year for orbit 10030, respectively.

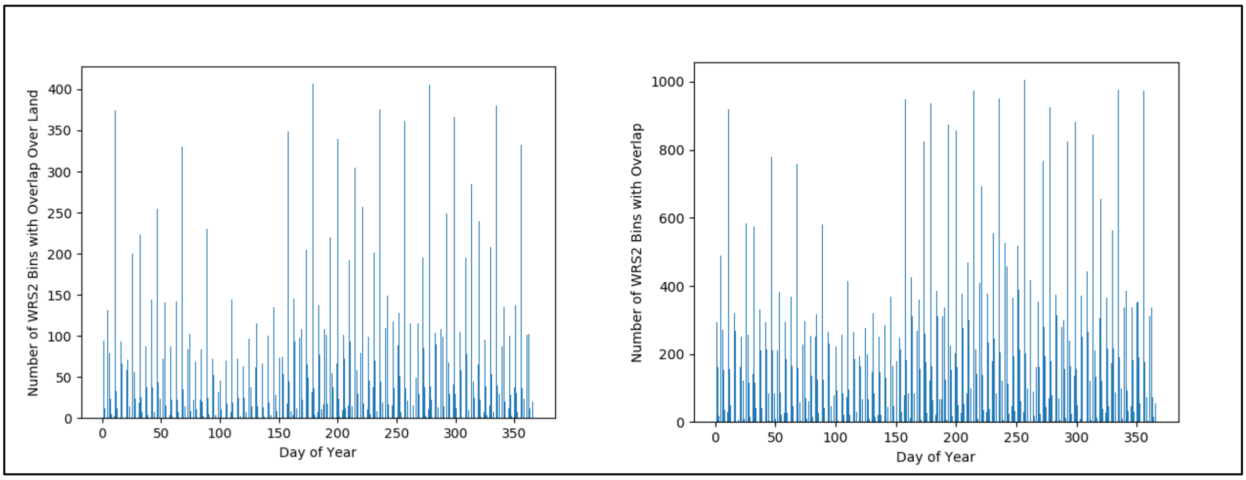

Figure 19 Number of WRS2 Bins with Overlap for Candidate 10030 Triple Collects

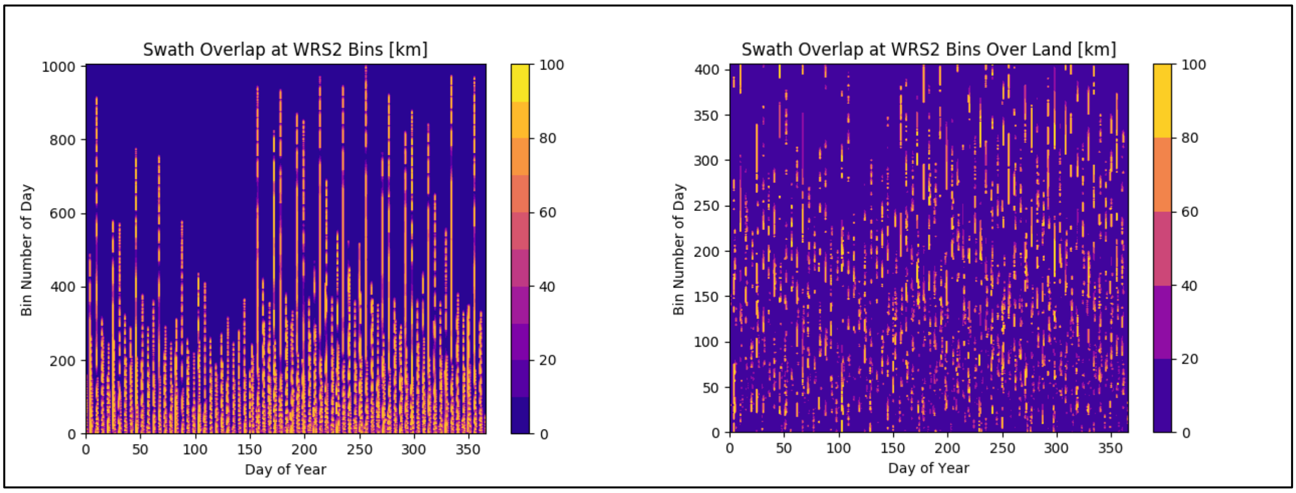

Figure 20 Swath Overlap of WRS2 Bins for Candidate 10030 Triple Collects

11.2.5.8 USGS orbit analysis

The focus of the orbit analysis in this study was to maximise the coincident collections between SCR and Landsat 8 plus Sentinel-2 A/B. In post study discussions between GA, USGS and UNSW personnel regarding SCR concept of operations and instrument development, USGS orbit analysis results were presented that summarised an investigation to determine maximum coincident collections between SCR and Landsat 8, Sentinel 2- A/B, as well as Planet SuperDoves (Flock 4-p) and CLARREO Pathfinder.

The results indicated that an orbit with altitude ~593 km and a LTDN of 10:15 AM provided the opportunity to obtain the largest number of coincident collections between SCR and each of the target sensors in this more diverse group of spacecraft[90].

As the concept of operations is refined, then candidate orbits will be finalised to inform the further development of the SCR instrument and system architecture.

11.3 Payload assessment

The SCR instrument requirements were summarised in section 11.1.3. SCR would deliver the capabilities either at a breakthrough (B) or target (T) level that would allow Australian industry to participate to the fullest extent possible in the instrument development process .

11.3.1 Payload performance

The SCR FOC will necessarily be a high-performance instrument in the same class as CLARREO Pathfinder and will require significant science community input and engineering expertise to develop. The radiometric and spectral accuracy requirements for SCR are as demanding as the best space-based state-of-the-art hyperspectral imaging spectrometers currently in operation.

There are several current and planned space-based hyperspectral missions. These include the EnMap (DLR-Deutches Zentrum fur Luft- und Raumfahrt), PRISMA (ASI –Agenzia Spaziale Italiana) and SHALOM (a joint ISA-Israeli Space Agency/ASI) missions. These missions deploy high performance hyperspectral imaging spectrometers to meet the needs of end-users across multiple disciplines and applications. A comparison of the performance of these systems along with the requirements for SCR are displayed in Table 28.

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[90] "USGS_Orbit selection for SCR'', results presented at the SCR Technical Interchange Meeting USGS/GA, 14 July 2021.

Table 28 Hyperspectral Imaging Spectrometer System performance comparison between SCR and other space-based systems

System Parameters	**SCR**	**EnMap**	**PRISMA**	**SHALOM**	**HyPixm**
Orbit – SSO (km)	600-700	653	615	640	660
Imaging mode	Pushbroom	Pushbroom	Pushbroom	Pushbroom	Pushbroom
GSD (m)	100	30	30	10 (PAN 2.5)	15
Swath (km)	40-60	30	30	10	16
VNIR spectral range (nm)	400-1000	420 - 1000	400-1010	400-1010	400-1100
SWIR spectral range (nm)	1000-2400	900 - 2450	920-2500	920-2500	1100-2500
Spectral resolution-FWHM (nm)	15 (B) / 10 (T)	8	10	10	10
Spectral sampling interval (nm)	10 (B) / 5 (T)	6.5	10	8	10
VNIR bands	60 (B) / 120 (T)	~ 90	~ 66	~ 66	~ 70
SWIR bands	140 (B) / 280 (T)	~ 135	~ 171	~ 171	~ 140
VNIR SNR (Threshold)-at reference radiance	> 150:1 (band dependent)	200:1 500:1 (@495 nm)	200:1 600:1 (@ 650 nm)	200:1 (400 –1000 nm) 600:1 (@ 650 nm) 400:1 @ 1550 nm 200:1 (1000-1750 nm) 200:1 @ 2100 nm 100:1 (1950 – 2350 nm)	250:1
On-orbit Radiometric accuracy (%)	5 (B) 3 (T)	5	5	4	TBC
NEDL (mW m^{-2} mm^{-1} sr^{-1})	0.01	0.05	0.1	TBC	TBC
Radiometric stability over 30 days(%)	0.2				
Dynamic Range (bits)	12	14	12	12	TBC
Compression (lossless)/compression ratio	1.6:1	JPEG2000 / 1.6:1	1.6:1	1.4:1	1.6:1
Revisit time (day)	TBD	4	4	4	4

Both PRISMA and EnMap have an on-orbit absolute radiometric requirement of 5% which is comparable to the initial Pathfinder SCR[91],[92]. Both systems have a spectral calibration accuracy requirement of 0.1 nm[93]. SCR will ideally provide a better level of radiometric stability and comparable radiometric accuracy performance and have similar spectral calibration requirements with more stringent on-ground and in-flight radiometric calibration requirements.

11.3.2 Payload calibration

The SCR mission objectives for calibration would be the same as for example CLARREO Pathfinder[94] or TRUTHS where SCR would conduct on-orbit SI-traceable calibration[95] of spectral scene radiance/reflectance at an improved accuracy over other sensors and to use that improved accuracy as a 'gold standard' reference for inter-calibration of other sensors such as Landsat, Sentinel-2, and others.

Accuracy and stability requirements for satellite measurements in the reflected solar and SWIR bands are necessarily stringent for climate and weather applications and satellite sensor cross-calibration. Calibration requirements that are traceable to SI standards would be imposed such that tools for characterizing the geometric, radiometric, and spectral performance of SCR and for generating correction parameters to be applied to the datasets can be adequately developed. As such, this requires exacting pre-launch and post-launch instrument calibration and validation.

The characterization and calibration of SCR would be planned and implemented in conjunction with the instrument development to meet the overall performance requirements. Since SCR requirements place much greater demands on the uncertainty of sources and delivery systems for calibration this necessitates the use of existing state-of-the-art facilities for on-ground calibration. In addition, on-board calibration subsystems whether these be passive-solar or active-spectral source based will be required to maintain very low uncertainties in radiometric output, uniformity, and stability.

Maintaining a valid set of instrument response function (IRF) calibration and correction parameters that account for any anomalies or overall performance degradation over time is an operational imperative for tracking the radiometric, spectral, and geometric response of the instrument. This mission critical activity begins with the pre-launch calibration and continues throughout the mission life with regularly scheduled in-flight calibration operations.

11.3.2.1 On-Ground Calibration

The goal of the on-ground calibration campaign is to establish a pre-flight IRF reference. Ground support facilities that provide high-accuracy and SI-traceable radiometric, spectral, and geometric stimuli provide the means to establish the IRF with a high degree of certainty prior to launch.

Establishing the baseline SCR performance on the ground is critical to mission success. Best practice methods for assessing instrument component and subsystem performance prior to and during assembly, alignment and instrument testing must be rigorously employed to understand the uncertainties in performance and to construct reliable performance error budgets.

The SCR would be calibrated and characterised at instrument level in a well-established facility which is explicitly designated for space-based optical instrument calibration. A facility such as NASA's GLAMR (https://glamr.gsfc.nasa.gov/) which provides the stable and accurate radiometric

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[91] Baur, S., et al., "Calibration and characterization of the EnMAP hyperspectral imager", Proc. SPIE 11151, Sensor, Systems, and Next-Generation Satellites XXIII, 111511B (10 October 2019); doi: 10.1117/12.2532715

[92] Camerini, M., et al., "The PRISMA hyperspectral imaging spectrometer: detectors and front-end electronics", Proc. SPIE 8889, Sensors, Systems, and Next-Generation Satellites XVII, 888917 (16 October 2013); https://doi.org/10.1117/12.2030409

[93] Meini, M., et al., "Hyperspectral Payload for Italian PRISMA Programme", Optical Payloads for Space Missions, John Willey and Sons, 2016 10.1002/9781118945179

[94] Thome, K., and Aytac, Y., "Independent calibration approach for the CLARREO Pathfinder Mission, Proceedings Volume 11130, Imaging Spectrometry XXIII: Applications, Sensors, and Processing; 111300B (2019) https://doi.org/10.1117/12.2529215

[95] Datla, R.U., et al., "Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing", J. Res. Natl. Inst. Stand. Technol. 116, 621-646 (2011).

and spectral sources (and will be used for the calibration of CLARREO Pathfinder) would be an ideal candidate for the on-ground calibration of both the SCR FOC (and the SCR PF if needed).

In addition to radiometric and spectral calibration, an image quality assessment at instrument level would also be performed where key parameters such the instrument imaging response functions (e.g. modulation transfer function) would be determined using an appropriate set of targets and delivery systems. In addition to the SCR image quality, the pointing of the instrument with respect to the spacecraft axes would be established so that geo-referencing requirements are met.

11.3.2.2 In-Flight Calibration

The goal of in-flight calibration is to correct for short and long-term changes in the SCR response due to the harsh conditions of the space environment. Although in the short-term, there may be very good repeatability in the IRF measurements, in a long time series of measurements the response will likely have an overall drift or localised anomalies.

Periodic in-flight calibration of all spectral channels provides the means to correct the instrument responsivity that accounts for the likely performance degradation of the optical and detector components, which can occur in the space environment. Internal calibration of the instrument as well as vicarious calibration campaigns imaging terrestrial and lunar sites and cross-calibration with other instruments (e.g. CLARREO Pathfinder, EnMap, PRISMA) should be performed to provide a comprehensive evaluation of the SCR response over the mission life.

An on-board calibration sub-system provides known and accurate radiometric input. The instrument response to these sources links every spectrometer terrestrial dataset and provides the means for conducting trend analysis to monitor spectrometer performance over time.

The on-board calibrators, vicarious calibration, and cross-calibration campaigns with other sensors in conjunction with the instrument performance models and laboratory calibration baselines provide the means to maintain a traceable instrument response as well as image product validation over the mission. This approach is summarised in Figure 21.

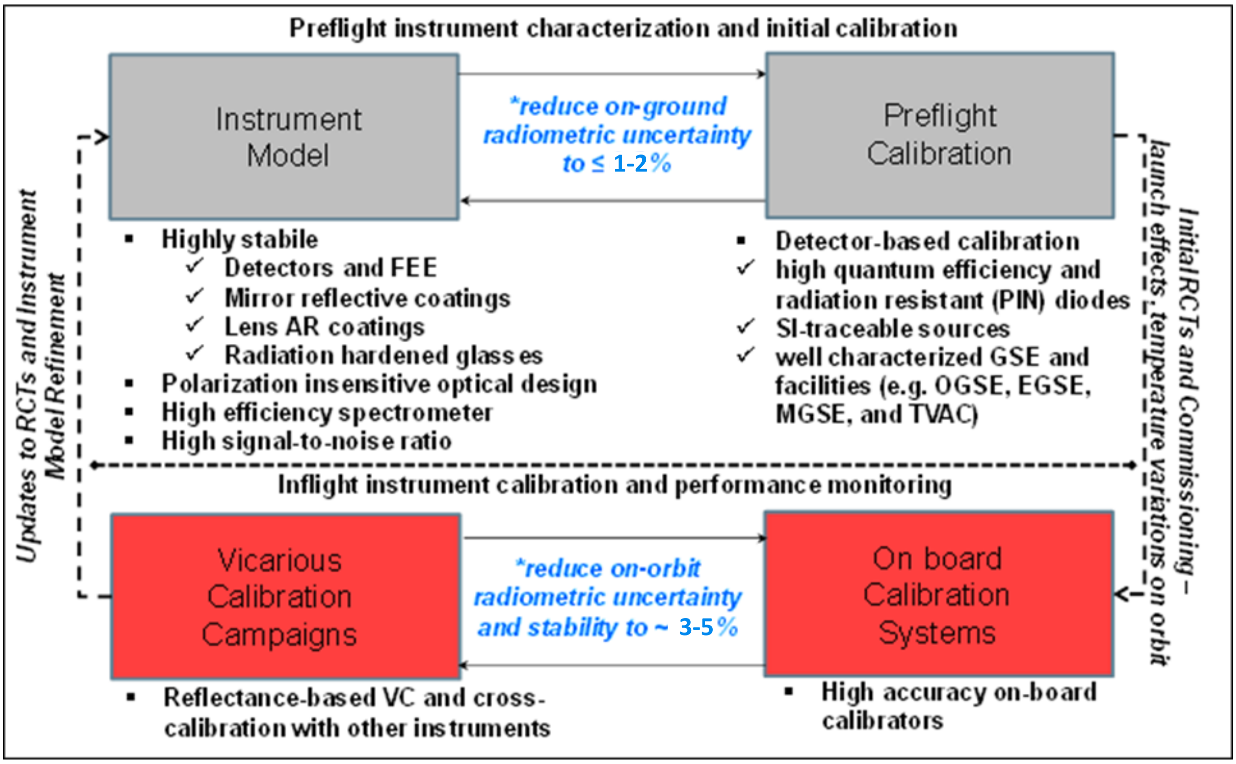

Figure 21 SCR lifecycle radiometric calibration approach overview

Typically, a solar calibration unit will be included as part of the instrument design. The sun provides a stable source, which establishes the absolute radiometric accuracy and stability assessments of the spectrometer during the mission life[96]. The solar calibration unit provides a full-aperture calibration of the entire optical chain from the optical system entrance aperture to the detectors to account for any changes in transmission and sensor response.

In addition, active LED lamp sources are used to provide an assessment of the spectrometer spectral response over time. The delivery system which is incorporated into the spectrometer design should provide an athermal environment for the sources as well as stable and steady drive current. Any diffusers should be protected from radiation and thermal variations when not deployed to maintain their stability. Despite these design practice implementations, the lamps themselves can change in colour temperature over time and diffuser material scattering properties can change due to the harsh space environment.

In addition to radiometric calibration operations, the acquisition of designated terrestrial targets would be used to assess the SCR in-flight measurement of spatial resolution parameters, including ground sample distance, far field response, edge response and modulation transfer function as well as geo-reference accuracy. These acquisitions would be part of normal calibration operations over the mission life[97].

11.3.3 Payload options

Several options were considered for a SCR PF and SCR FOC mission. A review of the currently available off the shelf instruments and those being designed for use to support the Sustainable Landsat Imaging program was conducted. The results are summarised in Table 29 which provides a checklist of performance capability against the preliminary requirements (Table 13). Green ticks indicate compliance with the observation requirements, red font indicates non-compliance. At this stage, no distinction is made between partial and non-compliance. For example, while the ANU VIS and Eartheye sensors provide a SNR >100 across all bands, they do not achieve the expected required SNR closer to 300 in some critical bands. This has not been analysed in detail, but should be done in a future design study.

Ball Aerospace in partnership with NASA is developing systems such as the REMI-AB and CHPS-AB instruments. These have recently completed airborne testing flights[98]. The CHPS sensor is the currently best available candidate for the SCR FOC.

Another possibility for use on the SCR PF is the Micro-HyperSpec imaging spectrometer from Headwall Photonics. This option would be investigated in the next phase of the project for inclusion on a SCR PF mission. The HyperSpec spectrometer series covers the VNIR, extended NIR and SWIR spectral ranges. These COTS spectrometers are configured with CCD, CMOS for the VNIR range, InGaAs for the extended VNIR range or MCT detector arrays for the SWIR range and provide 12–16-bit ADC and use the CameraLink high speed digital interface.

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[96] Baur, S., et al., "Calibration and characterization of the EnMAP hyperspectral imager", Proc. SPIE 11151, Sensors, Systems, and Next-Generation Satellites XXIII, 111511B (10 October 2019); doi: 10.1117/12.2532715

97 Pagnutti, M., et al., "Targets, methods, and sites for assessing the in-flight spatial resolution of electro-optical data products", Canadian Journal of Remote Sensing 36(5):583-601 2010.

98 https://www.ball.com/aerospace/newsroom/detail?newsid=124032

Table 29 Payload options performance overview

	Ball Aerospace CHPS	Headwall HyperSpec		ANU developments (can be combined)		Satellogic Nu-Sat
		VIS	SWIR	VIS	SWIR	VIS
Spectral range (nm)	✓	400-1000	900-2500	400-800	800-2500	400-900
Spectral resolution (nm)	✓	✓	✓	✓	✓ TBD	✓
Swath (km)	✓	?	?	10 - 30	10 - 20	125
Spatial resolution (m)	?	?	?	✓	✓	✓
Radiometric accuracy (%)	?	?	?	?	?	3 - 5
SNR	?	?	?	> 100	✓ TBD	~ 100
TRL	6/7	5/6	5/6	4	4	9

11.3.4 Payload data handling

The SCR spacecraft hyperspectral imager will generate large amounts of data depending on the duty cycle, number of spectral bands used, and other properties of the instrument itself. Table 30 presents an example of trade-off options with respect to GSD, and swath width of the imager for a notional case where the spacecraft altitude is 705 km and 200 spectral bands are transmitted to ground, with an orbital imaging duty cycle is set at 16.5% .

Table 30 Daily data volume estimate for various combinations of GSD and swath width

Daily data volume estimate for various combinations of GSD and swath width

Daily data volume [GB/d]	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	32	128	356	3208
20	64	257	713	6416
40	128	513	1426	12833
60	192	770	2139	19249
80	257	1027	2852	25665

The figures are based on the following assumptions:

- 16.5% duty cycle (worst case)
- 12 bits per pixel
- 200 spectral bands
- 705 km orbit altitude
- 75 min/day of ground station contact

The numbers in cells with grey background colour indicate configurations that exceed the limit imposed by existing ground segment data processing capabilities, which are in the order of ~500TB/year. Red background colour indicates configurations that exceed the expected maximum across-track detector size of 2000 pixels which is an estimate of the largest monolithic COTS CMOS array presently available. Development of a multiple detector-array focal plane assembly to cover larger fields of view is possible (e.g. MODIS, IKONOS, Landsat)[99] but technical feasibility would be limited within Australia due to the design, alignment and implementation complexities associated with a multiple-module FPA.

Once the instrument is selected, the swath width, GSD, number of spectral bands and other properties of the instrument would determine the final data volume per day the spacecraft would need to manage.

On board data handling will store the payload data into non-volatile memory with appropriate meta information such as timestamps and location telemetry. The data is then potentially compressed and sent to the high bandwidth radio transmitter for downlink. Special precautions and data handling architecture should consider how simultaneous reading and writing from non-volatile memory should

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[99] Kevin J. Malone, Ronald J. Schrein, M. Scott Bradley, Ronda Irwin, Barry Berdanier, Eric Donley, "Landsat 9 OLI 2 focal plane subsystem: design, performance, and status," Proc. SPIE 10402, Earth Observing Systems XXII, 1040206 (5 September 2017); https://doi.org/10.1117/12.2273058

be handled. This situation may arise when the spacecraft is imaging while downlinking data to the ground station.

11.3.5 Image data compression

Hyperspectral payloads produce vast amounts of data due to the large number of spatial and spectral samples contained in each datacube. In most cases, the data down-link rate and volume from a satellite to a ground terminal will be limited by the availability of on-board data storage, limitations in the data channel bandwidth and the duration of the temporal transmission window when the satellite has a line of sight to a ground station.

Reducing the amount of transmitted data is a critical mission issue that can be addressed using compression techniques. Since the mid-1990s when airborne HSI were flown, users and operators of these systems have been concerned with developing data compression and processing methods to manage the large amounts of image data [100]. There are many algorithms[101],[102],[103] which can be employed to allow for the extraction of the salient information in an image and its representation by fewer samples than in the original raw image. These include JPEG2000, wavelet, PCA and DCT-based algorithms to name a few. These algorithms are typically deployed in space-qualified ASIC[104], FPGA[105],[106] and GPU[107],[108] hardware rather than in software for speed and efficiency reasons.

Image compression removes redundant or non-relevant information and encodes what remains and reduces the amount of data that is transmitted. Hyperspectral image datasets can be many hundreds of Megabytes in size and various compression algorithm types have been implemented to manage the volume of data produced by space-based hyperspectral sensors[109].

The current image compression standard used by satellite developers for hyperspectral image data is the CCSDS-123.0-B-2[110]. Issue1 of the CCSDS-123.0-B standards focused on lossless compression of multispectral and hyperspectral images and was published in 2012[111]. This standard has been very successful and has already been adopted by several missions. Issue2 describes the closed loop quantization scheme to provide near-lossless compression while still supporting lossless compression.

The compression ratio (CR) of a given algorithm is a measure of the amount of data reduction and is expressed as a ratio of the size of the original image to the size of the compressed image. All current and planned space-based hyperspectral missions deploy image compression. For example,

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[100] Simmons, R., Brower, B., and Schott, J.," Data characterization for hyperspectral image compression", Proc. SPIE **3119**, Multispectral Imaging for Terrestrial Applications II, (19 September 1997); https://doi.org/10.1117/12.278946

[101] Yu, G., Vladimirova, T., and Sweeting, M., "Image compression systems on board satellites", Acta Astronautica, 64, 988-1105 (2009)

[102] Dusselaar, R., and Manoranjan, P., "Hyperspectral image compression approaches: opportunities, challenges and future directions: discussion", J. Opt. Soc. Am. A 34, 2170-2180 (2017).

[103] Puri, A., at al., "A comparison of hyperspectral image compression methods", Int. J. Comp. and Elec. Eng., **6** (6) (2014).

[104] Brower, B., et al., "Advanced space-qualified downlink image compression ASIC for commercial sensing applications", Proc. SPIE **4115**, 311-319 (2000).

[105] Caba, J., "FPGA-based on-board hyperspectral imaging compression: benchmarking performance and energy efficient against GPU implementations", Remote Sens., **12** 3741 (2020).

[106] Li, L., et al., "Efficient implementation of the CCSDS 122.0-B-1 compression standard on a space qualified field programmable gate array" in Journal of Applied Remote Sensing 7.1 (2013).

[107] Keymeulen, D., et al., "GPU lossless hyperspectral data compression system for space applications", 2012 IEEE Aerospace Conference, 2012, pp. 1-9, doi: 10.1109/AERO.2012.6187255.

[108] Diaz, M., "Real-time hyperspectral image compression onto embedded GPUs", in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 12, no. 8, pp. 2792-2809, Aug. 2019, doi: 10.1109/JSTARS.2019.2917088

[109] Dua, Y., et al., "Comprehensive review of hyperspectral compression algorithms", SPIE Optical Engineering, **59** (9), (2020).

[110] A. B. Kiely et al., "The new CCSDS standard for low-complexity lossless and near-lossless multispectral and hyperspectral image compression," in Proc. On-board Payload Data Compression Workshop, 1 –7 (2018).

[111] *Lossless Multispectral & Hyperspectral Image Compression*. Recommendation for Space Data System Standards, CCSD 123.0-B-1. Blue Book. Issue 1. Washington, D.C., CCSDS, May 2012.

EnMap uses a compression algorithm with a CR of 1.8, while HISUI claims a CR of 1.4 and SHALOM a CR of 1.6.[112]

The choice of the image data compression approach for SCR will need to be taken within the context of the data management architecture for the mission. The process can be a non-real-time one. The compression system should be able to compress in an orbital period the amount of data that could be downloaded in a single pass.

11.4 Satellite platform subsystems

11.4.1 Communications

The spacecraft shall have several communication channels, some capable of both uplink and downlink while others supporting only downlink functions.

The primary communication channel for telemetry and telecommand can be a low bandwidth channel supporting at least 9.6 kbps data rates in both uplink and downlink directions. The secondary or redundant telemetry and telecommand communication channel would be preferred and this communication channel shall also support uplink and downlink data rates of at least 9.6 kbps. The primary and secondary T+TC channels should use UHF and/or S-Band frequency bands and should provide omni-directional antennas so that communication with the spacecraft can be established whilst the spacecraft are in any orientation.

The payload downlink communication channel shall be a high data rate communication channel in the S-Band or preferably X-Band frequency range. These frequency ranges allow the use of existing ground station infrastructure hence greatly reducing the cost of obtaining the data from the spacecraft by leveraging existing infrastructure and partnerships.

The payload downlink channel requires a minimum bandwidth of 200 Mbps to allow downlinking sufficient volumes of data. This communication channel shall have some form of redundancy, even if it means the redundancy is bandwidth reduced.

11.4.2 Power

The spacecraft shall provide sufficient power generation capability to ensure the power budget remains positive throughout all the commissioning and nominal operations. The power generation shall be implemented using triple junction solar cells. Depending on the spacecraft bus and the payload power requirements, as well as the final mechanical configuration of the spacecraft, deployable solar arrays may be necessary.

The spacecraft shall provide power sufficient power storage capability to support spacecraft operations through eclipse periods and to supplement power generation sources in high power operations. Commonly used energy storage element are batteries, in lithium or other chemistries depending on operational and environmental requirements. The energy storage element shall be capable of supplying the required surge currents (peak and continuous) and shall be sized appropriately so that it is not discharged beyond safe limits during eclipse and high-power operations (this is typically a maximum discharge of 20% for lithium-based chemistries).

11.4.3 Flight software elements

The flight software of a spacecraft can be classified into two groups: core/platform software, and payload software. The platform software is closely integrated with the underlying electronics and hardware of the spacecraft. The payload software interfaces the payload to the platform OBC (for TT&C of the payload) and with the payload radio (for downlink of payload data). Well-functioning

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[112] Optical Payloads for Space Missions, ed. Qian, S., John Wiley and Sons (2016).

software is critical to mission success and can result in a total loss of mission if an error occurs. The following standards are relevant when delivering high quality software:

- ISO 49.140 (particularly ISO 14950)
- ISO 25010
- NASA-HDBK-2203
- NASA-STD-8739.8
- NASA-GB-8719.13

11.4.3.1 Platform software

The platform software is often (but not always) provided by the spacecraft bus provider. The capabilities of the software provided depend on what has been agreed upon via the contract. The platform software is required to enable operations of the spacecraft. Some common software elements include:

- Power/thermal management systems
- Fault detection, isolation, and recovery
- Control of any mechanisms or actuators (such as deployable solar panels, antennae, or thrusters)
- Spacecraft TT&C

11.4.3.2 Payload software

The payload software interfaces the payload sensor to the spacecraft bus and the payload radio. The ability to load a new software package whilst the spacecraft is in-orbit is highly desirable, as it allows for defect correction and feature additions to take place post-launch. We recommend ensuring that all relevant subsystems can be reprogrammed in-orbit.

11.4.3.3 Common procurement options

Various options for the scope and deliverables of the software package exist. Common options are listed in Table 31. The relative cost of the packages increases with included options.

Table 31 Software package overview and qualitative, relative cost

Software Package	Notes	Relative Cost
None	The spacecraft bus includes no software. The integrator is expected to write/provide the required software. The bus provider may assist by offering relevant technical information.	Nil
Drivers	The spacecraft bus comes with software drivers for each individual component in the bus. For example, a driver may be provided for the EPS, and another driver for the ADCS. These drivers are components and do not form a complete system.	$
Drivers and framework	This likely includes an operating system or similar framework. The framework is designed to integrate the drivers into a cohesive application. The integrator may need to the software to their TT&C requirements or make appropriate adjustments to the ground-based systems.	$$
Whole mission application	Drivers and framework, as well as any specific NRE required for the mission. This includes the integration of the payload software with the platform OBC, and any integration required between the payload OBC to the payload radio.	$$$$

11.5 Ground segment analyses

11.5.1 Ground station network

During the CDF study the following ground station sites were considered as possible candidates for the mission.

- GA Station, Alice Springs, NT, Australia (-23.758970, 133.881859)
- Hobart, TAS, Australia (-43.057600, 147.317783)
- Cape Ferguson, QLD, Australia (-19.269191, 147.054298)
- Learmonth, WA, Australia (-22.234866, 114.094383)
- USGS EROS, Sioux Falls, SD, USA (43.735932, -96.622455)
- SANSA, Hartebeesthoek, South Africa (-25.887705, 27.706159)
- Casey Station, Antarctica (-68.576664, 77.967653)
- KSAT, Svalbard, Norway (78.217, 15.65)

A preliminary analysis of the suitability of various combinations of these ground stations in a SCR ground station network has been performed. Figure 22 shows the coverage of each of the listed ground stations for an exemplary satellite in a 700km SSO.

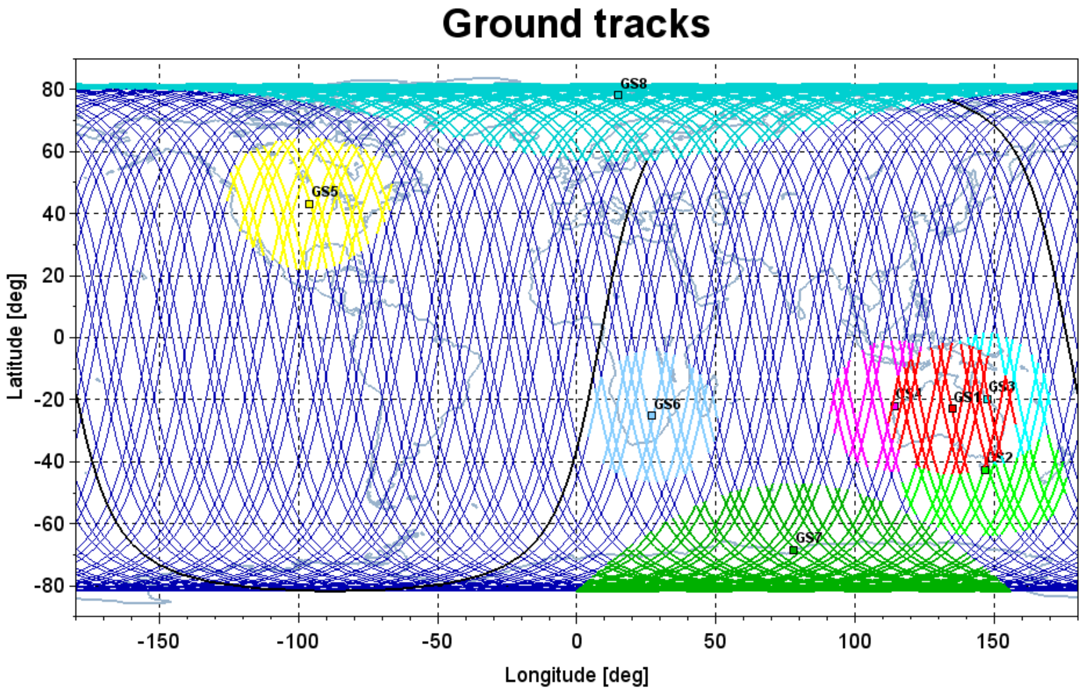

Figure 22 Orbital coverage of candidate ground stations

The resulting daily contact times are provided in Table 32.

Table 32 Ground station network options and associated daily contact times

Station combination	Total visibility (min/day)	Comment
Alice Springs	35	AUS only
Hobart	45	AUS only
Alice Springs, Hobart	52	AUS only
Alice Springs, Hobart, Christmas Island	82	AUS only
Alice Springs, Hobart, USA	102	
Alice Springs, Hobart, USA, South Africa	131	
Alice Springs, Hobart, USA, South Africa, Antarctica	223	
Alice Springs, Learmonth, Cape Ferguson	63	AUS only
Alice Springs, Learmonth, Cape Ferguson, USA	108	
Alice Springs, Learmonth, Cape Ferguson, USA, South Africa	141	
Alice Springs, Learmonth, Cape Ferguson, USA, South Africa, Antarctica	227	
Alice Springs, Learmonth, Cape Ferguson, Hobart	76	AUS only
Alice Springs, Learmonth, Cape Ferguson, Hobart, Antarctica	168	AUS only
Alice Springs, USA	75	
Alice Springs, USA, Antarctica	167	
Alice Springs, USA, Svalbard	229	

There is limited additional contact time gained by using multiple Australian stations; the benefit of a second Australian station is the redundant capability in case of a ground station failure, not an increase in contact time. Pairing an Australian station with an international station provides a significant increase in contact time. A USA station adds ~40 min/day, with an Arctic station adding ~147 min/day.

An Antarctic station adds ~90 min/day. Today, Antarctica has no undersea connectivity, due to the data rates of this mission backhaul via bandwidth-constrained satellite links would likely not be viable. An undersea cable would need to be provisioned if Antarctica is to be used for bulk payload data downlink. Such an Antarctica cable would need to be high availability as it would likely be the main ground station for this mission and the cable should have a high data rate to ensure timeliness of the data products. To meet the availability requirements, multiple TT&C capable ray dome shielded ground stations would be required in Antarctica for redundancy to allow for station maintenance and potential outages.

As shown above, an Arctic station adds a significant amount of contact time. Most Arctic stations are commercially operated, which would imply contractual and operating expenditure issues.

11.5.2 Ground segment cost assessment

The ground segment contracted cost is estimated at AUD0.4 M based on an FTE-year costed at AUD 200K. Details are provided in Table 33.

Table 33 Ground segment cost estimation details

Aspect	FTE	Duration [months]	FTE-months
Scoping / design	1	3	3
Development	1	6	6
Verification and validation	1	3	3
Maintenance and support	0.5	24	12
Total			**24**

11.5.3 Detailed downlink architecture

After the CDF study was completed, it was decided to investigate in greater detail the downlink capacity of various ground station configurations and radio options. The key findings were that

A data budget study conducted in Appendix C: Ground station analysis indicates that the mission could downlink up to 0.5-2 TB/day of raw payload data.

An X-band radio configuration is preferred due to a combination of the low relative cost, high performance, and high reliability of the solutions available. A two-radio X-band configuration can satisfy the target and breakthrough requirements for both the SCR pathfinder and the main mission.

A ground station configuration composed of Alice Springs, USGS EROS, and SANSA gives access to three of the four mission configurations using standard performance radios; two high-performance radios are required to meet all four mission requirements.

11.5.3.1 Key assumptions

In this trade study, it is assumed that the following conditions apply:

- Payload data compression system with a compression ratio of 1:6.1.
- Payload data storage system capable of buffering 100-4000 GB and supporting high speed read and write.
- Sufficient power to operate the spacecrafts radios, data processors and data storage is available.
- An attitude determination and control system (ADCS) is available to point the spacecraft as required.
- Size, weight, and power (SWaP) are unlikely to be limiting factors.
- The payload samples 200 bands at 12 bits/band, with a lossless compression ratio of 1.6:1 and an imaging duty cycle of 16.5%.

11.5.3.2 System configuration overview

Table 34 presents the data volume generated from the sensor as a function of the GSD and number of samples across a given swath. It is colour coded based on the daily data volume which can be supported by various ground station options and radio configurations. An overview of the configurations is given below with further information available in Appendix C: Ground station analysis.

Green (top left):

- Readily attainable solution based on today's technology, high TRL, low complexity solution
- Two/three continental ground stations
- COTS high TRL X-band radio and antenna (~500 Mbps, space-system cost $100k-$500k)

Yellow (bottom middle):

- Solution attainable or likely to be attainable in the next two years, medium TRL, medium complexity solution
- Ground stations paired with an Arctic or Antarctic station
- Multiple COTS X-band radios and antennas (~1 Gbps, space-system cost $500k-$1000k)

Red (far right):

- Solution possibly attainable in the next two years, low TRL, high complexity solution
- Ground stations paired with Arctic and Antarctic stations, or an in-orbit X-band/Ka-band/optical relay network
- COTS X-band radio and antenna, COTS Ka-band radio and antenna, or COTS optical communication system (~10 Gbps, space-system cost $1000k-$5000k)
- Fibre optic submarine cable to Antarctica, and/or the deployment of an optical ground station network

Table 34 Data generated per day for various sensor configurations based on GSD and Swath

Daily data volume [GB/d]	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	32	128	356	3208
20	64	257	713	6416
40	128	513	1426	12833
60	192	770	2139	19249
80	257	1027	2852	25665

The figures are based on the following assumptions:

- 16.5% duty cycle (worst case)
- 12 bits per pixel
- 200 spectral bands
- 705 km orbit altitude

The numbers presented scale linearly with collection duty cycle and number of bands sampled, and quadratically with swath width and GSD.

These swath width and GSD configurations in the green and yellow sections are feasible for a spacecraft utilizing current technology that is readily available on the commercial market or expected to be within two years. TRL's are typically in the range of 5-9. Red regions are not expected to be attainable based on current TRL and availability within the next two years.

11.5.3.3 Derived downlink rate requirements

Table 35 presents the minimum payload data downlink rate required to satisfy the data budget given in Table 34, parameterised by ground station configuration, swath width, and GSD. Possible space-craft solutions that satisfy the minimum data rate requirements are then explored with a brief assessment of their viability based on key selection criteria.

Table 35 Effective downlink rate required to meet the data budget for given mission configurations

Mission	Swath (km)	GSD (m)	Required downlink rate (Mbps) to meet data budget					
			AS EROS	AS EROS SANSA	AS EROS KSAT	AS EROS AN	AS EROS KSAT AN	In-orbit relay
SCR								
Breakthrough	20	100	103	56	31	36	21	10
Target	60	100	415	227	125	146	84	41
MMI								
Breakthrough	40	30	1153	631	349	406	236	115
Target	60	30	4613	2524	1398	1626	944	461

Identifier	Ground station name
AS	Alice Springs, Australia
SF	USGS EROS Sioux Falls, USA
KSAT	Svalbard, Norway
AN	Casey Station, Antarctica
SANSA	Hartebeesthoek, South Africa

The payload configurations used to determine the rates defined above are described in Appendix C: Ground station analysis.

11.5.3.4 Required downlink data rates to satisfy mission data budgets

Table 36 through Table 41 present the minimum effective downlink rate that is required to downlink all the data collected during a day for the different swath width configurations. A compression ratio of 1.6:1 is assumed. The data is received without overhead and error correction codes. A ground station efficiency of 80% has been assumed.

The downlink data rates for most mission configurations can be met with current radios or those anticipated on the market in the next 2-3 years. The green fields indicate that the configuration is feasible with an effective downlink rate of 415 Mbps for SCR, the yellow fields indicate that the configuration is feasible with an effective downlink rate of 1400 Mbps for the MMI.

Red fields are considered harder to achieve; some are feasible given a 3-4 Gbps downlink rate, whereas others (> 10 Gbps) are pushing the limits of current/near-future technology with an appropriate TRL. The downlink rates for SCR and the MMI have been selected based on hardware availability, documented in the sections below.

Table 36 Data rates for station configuration Alice Springs and USGS EROS

Min downlink rate required [Mbps]		**Visibility [min/day]**	**63.07**	
AS_SF	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	51.90	207.59	576.65	5189.83
20	103.80	415.19	1153.30	10379.66
40	207.59	830.37	2306.59	20759.33
60	311.39	1245.56	3459.89	31138.99
80	415.19	1660.75	4613.18	41518.66

Table 37 Data rates for station configuration Alice Springs, USGS EROS and KSAT

Min downlink rate required [Mbps]		**Visibility [min/day]**	**208.01**	
AS_SF_KSAT	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	15.74	62.94	174.84	1573.57
20	31.47	125.89	349.68	3147.14
40	62.94	251.77	699.36	6294.28
60	94.41	377.66	1049.05	9441.43
80	125.89	503.54	1398.73	12588.57

Table 38 Data rates for station configuration Alice Springs, USGS EROS, KSAT and Casey

Min downlink rate required [Mbps]		**Visibility [min/day]**	**308.09**	
AS_SF_KSAT_AN	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	10.62	42.50	118.05	1062.42
20	21.25	84.99	236.09	2124.83
40	42.50	169.99	472.18	4249.66
60	63.74	254.98	708.28	6374.50
80	84.99	339.97	944.37	8499.33

Table 39 Data rates for station configuration Alice Springs, USGS EROS and SANSA

Min downlink rate required [Mbps]		**Visibility [min/day]**	**115.27**	
AS_SF_SANSA	**GSD [m]**			
Swath width [km]	**100**	**50**	**30**	**10**
10	28.40	113.59	315.52	2839.66
20	56.79	227.17	631.03	5679.31
40	113.59	454.35	1262.07	11358.63
60	170.38	681.52	1893.10	17037.94
80	227.17	908.69	2524.14	22717.25

Table 40 Data rates for station configuration Alice Springs, USGS EROS and Casey

Min downlink rate required [Mbps]		Visibility [min/day]	178.88	
AS_SF_AN	GSD [m]			
Swath width [km]	100	50	30	10
10	18.30	73.19	203.32	1829.86
20	36.60	146.39	406.63	3659.71
40	73.19	292.78	813.27	7319.43
60	109.79	439.17	1219.90	10979.14
80	146.39	585.55	1626.54	14638.85

Table 41 Data rates with laser communication to single ground station

Min downlink rate required [Mbps]		Visibility [min/day]	630.00	
In-orbit relay	GSD [m]			
Swath width [km]	100	50	30	10
10	5.20	20.78	57.73	519.55
20	10.39	41.56	115.46	1039.10
40	20.78	83.13	230.91	2078.21
60	31.17	124.69	346.37	3117.31
80	41.56	166.26	461.82	4156.42

It is assumed that the relay satellite/network of satellites has gigabit connectivity to a ground station with high availability, such that it does not limit the downlink capability of the SCR.

11.5.3.5 System configuration selection

In this section four system configuration suggestions are listed. One configuration with some options is provided for the SCR target using a single X-band radio. For the MMI target, a feasible configuration featuring two COTS or custom X-band radios is provided, as well as two configurations featuring emerging technologies such as Ka-band and optical communications. The latter two configurations however feature greater uncertainties in ground station access, due to atmospheric conditions affecting the communication channels and ground station support.

Further details into the ground station, radio, antenna, and amplifier options are found in Appendix C: Ground station analysis.

11.5.3.5.1 System configuration 1 – SCR target

Imager configuration

- Swath width: 80 km
- GSD: 100 m
- Key assumptions from Section 11.5.3.1

Spacecraft

An X-band radio such as the Syrlinks EWC30-NEXT, the Tethers SWIFT-HB, or the Tesat Integrated Data Downlink Transmitter all provide data rates that meet the minimum required data rate of 415 Mbps when used in a two-ground station configuration. Appropriate adaptive FEC (forward error correction) must be used, such that the BER (bit error rate) is minimised on the lowest parts of the communication pass, and no unnecessary bandwidth is used on FEC during the higher parts of the communication passes. A single radio channel is sufficient, therefore only one unit of the above radios is required. An advantage with selecting the Tethers SWIFT-HB is, that this radio will provide sufficient data rates for the MMI.

With a 11-12 dBi antenna, such as the Anywaves X-band Payload Telemetry Antenna or Endurosat X-band Patch Antenna in 2X2 configuration, sufficient data rates can be achieved using a 30-36 dBm power amplifier, such as the Qorvo TGA2700. Alternatively, the Qorvo QPA2612 can be operated with an appropriate input power level to output 36 dBm albeit at a reduced PAE. It is suggested to utilize one antenna mounted to a mechanical gimbal. The 40-degree beam width of both antennas reduce the pointing accuracy requirements of the attitude control system and gimbal.

To enhance national capabilities and maintain full control over the radio system, a custom X-band transmitter could be developed. The custom solution should be designed and tested to raise the TRL in the SCR mission to qualify for use in the MMI. The custom developed radio could be integrated alongside a COTS radio solution to provide a fallback. This however comes at the cost of increased mass and size of the SCR spacecraft.

Ground system

This configuration selects a ground station at Alice Springs, Australia, and a ground station at Sioux Falls, USA. Both ground stations support X-band reception and are connected into network backbones that have sufficient connectivity to move the received data with low latency to a long-term data storage facility. The ground station at Alice Springs features two 9-metre parabolic antennas, allowing simultaneous downlinks from the main satellite and follower Imaging near ground stations might require that the spacecraft can simultaneously image and downlink, requiring a wide beamwidth or steerable antenna.

11.5.3.5.2 System configuration 2 – MMI target X-band

Imager configuration

- Swath width: 80 km
- GSD: 30 m
- Key assumptions from Appendix C: Ground station analysis

Spacecraft

An X-band radio such as the Syrlinks EWC30-NEXT, the Tethers SWIFT-HB, or the Tesat Integrated Data Downlink Transmitter all provide data rates that meet the minimum required data rate of 1398 Mbps when used in a three-ground station configuration. Two radios are required to achieve the data rates required for the given imager configuration. This can be achieved by utilizing two radios in a left-hand circular polarisation (LHCP) and right-hand circular polarisation (RHCP) configuration. Operating with two downlink channels doubles the effective data rate; this usage is well-known and a generally accepted practice. The two polarisations are independent and do not interfere with each other from an RF perspective, allowing the same spectrum to be used for each channel. This ensures only feasible bandwidths are required and that the system adheres to the spectrum band plan.

A radio with ACM allows a significantly smaller power amplifier to be utilized, since the data rate can be lowered to sustain acceptable BER levels during the low elevations of the pass and be raised as the elevation increases. It is in this case crucial that the maximum data rate supported by the radio is sufficiently high.

When using two radios, the Tethers SWIFT-HB, Tesat integrated Data Downlink Transmitter and custom solution all provide a sufficiently high data rate to achieve the minimum required data rate. The latter two radios support ACM, which allows downlinking at lower data rates at low elevations or when large >9m parabolic apertures are not available on the ground.

Using an 18 dBi antenna, such as the Endurosat X-band Patch Antenna in 4X4 configuration, a raw data rate of 900 Mbps can be achieved at 2000 km slant range and over 2000 Mbps can be achieved at 800 km slant range using a 33 dBm power amplifier. This is for each radio. Thus, at a high elevation, the combination of two radios can achieve over 4000 Mbps raw data rate. This results in 2000 Mbps effective when using rate ½ convolutional coding. Increasing the power amplifier output power to 36 dBm doubles this data rate.

A single narrow beamwidth dual feed patch antenna mounted on a mechanical gimbal is recommended. This reduces the power usage compared to a switched antenna array and reduces the requirements of the power amplifier significantly.

Ground system

This configuration selects a ground station at Alice Springs, Australia, a ground station at Sioux Falls, USA, and a ground station at Svalbard, Norway. All ground stations support X-band reception and are connected into network backbones that have sufficient connectivity to move the received data with low latency to a long-term data storage facility. The usage of an Australian ground station implies that the spacecraft must have the ability to simultaneously image and downlink, requiring a wide beamwidth or steerable antenna.

This configuration may meet the required data downlink rate by involving SANSA instead of KSAT, however there will be effectively no contingency. A KSAT station could be exchanged with a ground station at Casey Station with minimal difference in the data downlink capability.

11.5.3.5.3 System configuration 3 – MMI target optical communications

Imager configuration

- Swath width: 80 km
- GSD: 30 m
- Key assumptions from Appendix C: Ground station analysis

Spacecraft

A single laser communication system such as the Tesat TOSIRIS or the Xenesis Xen-Hub is suitable to achieve in-pass downlink rates of 10 Gbps. These systems are relatively new and are only beginning to build flight heritage now. There are often spacecraft pointing/stability requirements associated with the use of optical systems due to their narrower beamwidths compared to typical RF solutions. An initial analysis indicates that the ADCS requirements for a laser downlink are likely to be captured by the requirements set by the imaging payload.

Additional on-board data storage may be required to provide buffers for time periods where no reliable contact can be made with the ground stations due to weather conditions.

Ground system

Of the prospective ground station sites identified, only KSAT are currently trialling an optical ground station capability. Candidate sites are Alice Springs, Australia, and a ground station at Sioux Falls, USA. These two sites provide sufficient contact time to meet the required data downlink per day. Climate conditions such as humidity, cloud cover and rainfall must be considered since these can drastically affect the communication times.

11.5.3.5.4 System configuration 4 – MMI target Ka-band

Imager configuration

- Swath width: 80 km
- GSD: 30 m
- Key assumptions from Appendix C: Ground station analysis

Spacecraft

A single Ka-band communication system such as the Tesat Gigabit modulator which is suitable to achieve in-pass downlink rates of 4 Gbps. While still an emerging technology on small spacecraft, multiple COTS solutions are publicly available. Pointing requirements for the antenna are higher than for X-band communications but are significantly more relaxed than the requirements for optical communications.

Additional on-board data storage may be required to provide buffers for time periods where no reliable contact can be made with the ground stations due to weather conditions.

Ground system

The KSAT ground station supports Ka-band downlinks, and the SANSA ground station features a 13.2m Ka band antenna. The Alice Springs 9m parabolic antennas and Sioux Falls 10m antennas can be equipped with Ka-band feeds.

11.5.4 Processing pipeline

Table 42 provides an overview of elements in the processing pipeline together with an indication of the responsible entity for software development and operations of each element.

Table 42 Overview of processing pipeline elements

Task	Software development	Operations	Notes
MoC/ TT&C	Contractor	Contractor	
Ground Station	GA/Partner	GA/Partner	In-network Predefined TT&C commands sent by contractor
Stitcher	GA	GA	In-network
L0	Contractor	GA	In-network Collections: Ground station telemetry, mission telemetry
L1	GA	GA	In-network Open product Collections: L1 product
L2 (ARD)	GA	GA	In-network Open product and code Option 1 collections: CARD4L surface reflectance, L2 cross-calibration product Option 2 collections: CARD4L surface reflectance, L2 cross-calibration product, bushfire fuel ancillary, L2 bushfire fuel product, water quality ancillary, L2 water quality product, L2 minerals indices
L3	GA/Partner	GA	In-network Open product and code Option 1 collections: L3 cross-calibration product Option 2 collections: L3 cross-calibration product, L3 bushfire fuel product, L3 water quality product, L3 minerals indices
Data distribution for L1/L2/L3	GA	GA	Via GA or AusCopHub

11.5.4.1 Processing level definition

Level 0

Level 0 (L0) data is raw or unprocessed instrument and payload data at full resolution and should contain both instrument and satellite (ephemeris, time synchronisation, satellite attitude, thermal, calibration) data to allow processing to Level 1. Not all satellite missions and instruments provide a full set of the required parameters to fully radiometrically and geometrically correct the data to the same Level 1 maturity level.

A SCR mission will utilise a hyperspectral sensor, which will produce a great deal more data than a multi-band mission, but Level 0 will be basically the same regardless of the satellite mission type.

Level 1

Level 1 (L1) data are radiometrically and geometrically corrected to top of atmosphere (TOA) radiance values and have pixel level georeferencing, or at least this is the goal of well-defined and funded Earth observation mission such as MODIS, Landsat, and Sentinel-2. With these types of missions, Level 1 is divided into sublevels A and B. Level 1A data have been geometrically corrected and Level 1B data are radiometrically corrected Level 1A data.

Landsat 8 has 3 sublevels defined as L1GS, L1GT and L1TP. The GS level is radiometrically and geometrically corrected based on the satellite data only, GT incorporates the use of a digital elevation model (DEM) to correct for relief displacement of pixels and the TP sublevel also incorporates ground control point correction to correct for topographic displacement.

Two hyperspectral missions of note are Hyperion and the Hyperspectral Imager for Coastal Ocean (HICO). Hyperion, a USGS mission was available as L1R data (radiometrically corrected only), but this was replaced in the archives with L1T data, which has geometric and terrain corrections applied as well. The HICO mission, a NASA operated satellite onboard the International Space Station (ISS) followed the NASA L1A/L1B standard.

Level 2

Level 2 (L2) data are derived geophysical products at the same resolution and time as the Level 1 input data. This means that for a pixel in a L1 raster file, which has a georeferenced position, there is a geophysical pixel value with the same georeferenced position. Converting the Level 1 radiance value to reflectance or applying further corrections such as atmospheric correction, NBAR and terrain correction, at the same georeferenced position, qualifies as Level 2 processing. This extension to further processing reflectance values which removes any systematically induced change in reflectance is increasing being referred to as Analysis Ready Data (ARD). If the reflectance or ARD values are further processed to a product, such as Normalised Difference Vegetation Index (NDVI), these are still referred to as Level 2 products if the georeferencing matches the Level 1 product.

Level 2 processing of an SCR or any hyperspectral sensor can prove more challenging due to the construction of hyperspectral sensors as opposed to multi-band sensors. Hyperspectral sensors can use a diffraction grating or prism based dispersing element that must be precisely aligned with the sensor pixel grid otherwise spectral distortion (e.g. keystone or smile) can make atmospheric correction more difficult. This was a significant issue with Hyperion data where the developers found a significant difference between the on-ground measured spectral distortion and the on-orbit values [113][114]. A calibration lab in space such as TRUTHS will allow these post-launch spectral corrections to be applied to an SCR missions.

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[113] Pearlman, J.S., et al., "Hyperion, a space-based imaging spectrometer," IEEE Trans. Geosci. Remote Sens. 41, 1160-1173 (2003)..

[114] Neville, R.A., "Detection of spectral line curvature in imaging ""spectrometer data", Proc. SPIE 5093, 144-154 (2003)

Level 3

NASA Earth data states that Level 3 (L3) data is variables mapped onto a uniform space-time grid, usually with some completeness and consistency. Level 3 products are generally merged products, such as a spatially averaged product over a given temporal window, which will provide cloud-free imagery of that product.

11.5.4.2 Potential standards

The SCR mission would use a variety of best practice EO community standards for the L1/L2/L3 processing pipeline. Likely specific standards include:

- Open licencing standard: Latest version of the Creative Commons Attribution License (CC-BY)
- Metadata standards: Latest version of ISO 19131 & 19115/2 at a minimum
- File format standard: Latest version of the Cloud Optimized GeoTIFF (COG)
- Distribution standards: Latest versions of the SpatioTemporal Asset Catalog (STAC) and Open Geospatial Consortium Web Coverage Service (OGC WCS)
- Analysis Ready Data standards: Latest version of the CEOS Analysis Ready Data for Land (CARD4L) standard

11.5.4.3 Archival strategy

The SCR mission intends to be fully compliant to the Australian Archives Act 1983. This would likely be achieved with:

- Ground station telemetry and mission telemetry: Stored on dual copy spinning disk of a commercial cloud, tape storage of a commercial cloud and Geoscience Australia managed offsite tape storage. In addition, both collections would be stored within the United States Geological Survey archives.
- L1-L3 collections: Stored on dual copy spinning disk of a commercial cloud only as they can be reproduced from the ground station telemetry and mission telemetry.

11.5.4.4 Mission storage estimates

Based on the above processing pipeline overview table the following number of collections would be created by the mission:

- Level 0: 2 collections
- Level 1: 1 collection
- Level 2:
  - Option 1: 2 collections
  - Option 2: 7 collections
- Level 3:
  - Option 1: 1 collection
  - Option 2: 4 collections

Assuming the following inputs:

- Option 1: 100 metre GSD, 40km swath, 200 bands, 12 bits
- Option 2: 30 metre GSD, 40km swath, 200 bands, 12 bits

This produces the following estimates:

- New telemetry per satellite per day (as defined in Section 11.3.4)
  - SCR: 128GB
  - MMI: 1426GB
- L0 collections (Ground station telemetry and mission telemetry):

  - 20% margin added to ground station collection to account for overlap
  - Three copies of both mission and ground station archives to meet the requirements of the Australian archives act
  - No compression on telemetry
  - SCR: 103 TB of telemetry (GS and mission) per satellite per year
  - MMI: 1147 TB of telemetry (GS and mission) per satellite per year
- L1-L3 collections (Only one high availability copy needed due to reproducibility from telemetry):
  - Compression halves all L1-L3 storage
  - SCR: 128GB per day x 4 collections / 2 for compression = 93 TB of products per satellite per year
  - MMI: 1426GB per day x 12 collections / 2 for compression = 3123 TB of products per satellite per year
- Total (L0-L3)
  - SCR: 196 TB per satellite per year
  - MMI: 4269 TB per satellite per year

11.6 Programmatic aspects analyses

11.6.1 Environmental qualification campaign costing

The NSTF is baselined for a cost estimate of an environmental qualification test campaign for the SCR mission. At this stage, the NSTF can only provide limited shock testing support, which is strongly dependant on the size and mass of the spacecraft as well as the required shock load. Alternative test houses exist, such as VIPAC with sites in Brisbane, Sydney, Melbourne, Adelaide, and Austest Laboratories with sites in Sydney, Melbourne, Adelaide, provide shock testing services, which are capable of filling in the gap to complete local environmental qualification testing capabilities within Australia. VIPAC and Austest further provide vibration test services and may be considered as an alternative test house, should the NSTF facilities not be capable of meeting the vibration test qualification requirements. However, consideration shall be given to any cleanliness requirements related to the test space and storage space This may incur additional costs if workspace modifications are required to ensure safe handling of the spacecraft.

Table 43 and Table 44 contain estimates for facility access cost and a detailed estimate of the environmental test effort needed for the SCR mission.

Table 43 NSTF daily access costs

Item	ROM Cost [AUD]
NSTF facility daily rate (7 hrs)	2500
NSTF cleanroom daily rate	500
NSTF cleanroom storage day rate	50

Table 44 SCR Environmental Qualification Test campaign ROM cost

SCR Mission Environmental Qualification Tests	ROM Cost [AUD]
STM shock test (2 days) @ VIPAC or Austest	6000
STM vibration test (2 days) @ NSTF	5000
EM thermal cycling (5 days) @ NSTF	12500

EM qual shock (1 day) @ NSTF	6000
EM qual vibe (2 days) @ NSTF	5000
EM EMC test (3 days) @ NSTF	7500
EM Vacuum Thermal Balance Testing (6 days); 24/7 operation incurs factor 3 on daily rate @ NSTF	45000
FM Vacuum Thermal cycling + bakeout (12 days); 24/7 operation incurs factor 3 on daily rate @ NSTF	90000
FM acceptance vibration testing (3 days) + cleanroom storage @ NSTF	5150
EM mass properties measurements inside cleanroom (2 days) @ NSTF	6000
FM mass properties measurements inside cleanroom (2 days) @ NSTF	6000
Total ROM cost	**194150**

11.6.2 Australian-made satellite platform cost estimate

For an Australian organisation to develop a microsat spacecraft bus suitable for the SCR mission, the following costs listed in Table 45 were estimated.

Table 45 Cost estimate for an Australian-made micro-satellite bus

			Cost	QTY/FTE	Years	TOTAL
Spacecraft Bus	**Labour**	Project Management	AUD 200k	1	3	AUD 600k
		Systems Engineering	AUD 200k	1	3	AUD 600k
		Electrical/RF	AUD 200k	4	2	AUD 1,600k
		Flight Software	AUD 200k	4	2	AUD 1,600k
		Mechanical/AIT	AUD 200k	4	2	AUD 1,600k
		ADCS	AUD 200k	1	2	AUD 400k
		Operations	AUD 200k	2	2	AUD 800k
		Administration /Finance	AUD 200k	1	3	AUD 600k
		TOTAL		18	3	AUD 7.8M
	Hardware, consumables,	Mechanical, incl. GSE	AUD 500k	1		AUD 500k
		Electrical & RF, incl. GSE	AUD 1,000k	1		AUD 1,000k
		ADCS	AUD 1,000k	1		AUD 1,000k

		Operations	AUD 50k	1		AUD 50k
		Flight Software	AUD 50k	1		AUD 50k
		Assembly, Integration, Testing	AUD 100k	1		AUD 100k
		TOTAL				AUD 2.7M
Launch estimate		Momentus				AUD 3.25M
		RL electron				
		Gilmore Space				
COMBINED TOTAL						**AUD 13.75M**

Labour costs were based on the estimated engineering effort to develop a microsat bus over 2 years, with Project Management, Systems Engineering, and Administration/Finance costed over 3 years. The cost of one Full-Time Equivalent (FTE) staff was approximated at AUD 130K per year salary (super-annuation included), with 50% extra for over-head costs.

Other costs were based on the estimated hardware, software, consumables, materials, and expenses needed to develop a microsat bus over a 2-year period.

Launch costs included integration with launch vehicle or parent satellite and launch into the destination orbit.

11.6.3 Commercial satellite platforms

The study investigated the suitability of commercially available satellite platforms to achieve the mission objectives. This was done in two steps:

1. In the first step, publicly available information from the internet was used to identify suitable candidates and assess their ROM cost.
2. In a second step, a subset of potential vendors was contacted with a request for information (RFI) to substantiate the publicly available information.

These two steps and their results are described in further detail in the following sections.

The general conclusion from this work package is that a COTS option would reduce the overall cost for the initial SCR missions by AUD 2.8M – 5.7M compared to the development of an Australian capability. As Australian maturity progresses, this difference is expected to shrink.

11.6.3.1 Assessment of publicly available information

A list of suitable candidate satellite platforms has been created based on engineering expertise and data sheet information publicly available. Suitability has been determined based on the definition of the backbox payload requirements as defined in section 11.1.4. For those platforms it was then tried to find publicly available information of their cost. The goal of this exercise is to derive a cost frame for the satellite bus component. Results of this exercise are summarized in Table 46.

In conclusion, the satellite bus for a spacecraft in the desired mass range can be expected to cost around USD 5M based on this assessment with a substantial uncertainty and the possibility of further increased cost in case of including further mission elements in the purchase order.

Table 46 Publicly available cost information on small satellite platforms

Manufacturer	Platform	Cost	# of satellites	ROM cost per satellite	Reference	Comments
RocketLab	Photon	USD 10M	1 launch incl 1 Photon		NASA Spaceflight website[115]	
Blue Canyon Technologies	X-Sat	USD 14.2M USD 99.4M	4 20	USD 3.5M USD 5M	Space News Feed website[116] Space News website[117]	BCT recently acquired by Raytheon Inc.
SSTL	150	USD ~238M	1	USD 238M	Space Tech Asia website[118]	Includes training Thailand to space
	NovaSar 1	GBP 21M	1			
York Space Systems	S-Class	USD 94M	10	USD 9.4M	Space News website[119]	Includes payload (data relay) and intersatellite comms.
	S-Class	USD 12.8M	1	USD 12.8M	Space News website[120]	Tetra-3 mission for USAF.
	S-Class	USD 1.2M	1	USD 1.2M	Space News website[121]	Company advertised cost for platform.
Berlin Space Technology	Kent Ridge	EUR 5M		EUR 5M	Handelsblatt[122]	LEOS-50 platform Includes launch costs but this is not the platform we need (LEOS-100)

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[115] https://www.nasaspaceflight.com/2020/09/rocket-lab-debuts-photon/

[116] https://www.spacenewsfeed.com/index.php/news/4921-blue-canyon-technologies-announces-phases-2-and-3-contract-win-for-darpa-s-blackjack-program

[117] https://spacenews.com/blue-canyon-technologies-could-produce-up-to-20-satellite-buses-for-darpas-blackjack/

[118] https://www.spacetechasia.com/thailand-selects-airbus-for-theos-2-satellite-total-budget-238-million/

[119] https://spacenews.com/lockheed-martin-york-space-win-contracts-to-produce-20-satellites-for-space-development-agency/

[120] https://spacenews.com/york-washington-office/

[121] https://spacenews.com/u-s-military-electron-launch-first-test-for-york-satellite/

[122] https://www.handelsblatt.com/english/companies/satellite-launch-cheap-satellites-for-the-world/23508232.html?ticket=ST-8463599-WIdEfXoJgNlSazrPKr7V-ap3

Manufacturer	Platform	Cost	# of satellites	ROM cost per satellite	Reference	Comments
	EgyptSat-1	USD 20M			AAG.org website[123]	20M is total cost program, not just satellite. Platform is LEOS-50 BST
Ball Aerospace and Technology Corp	BCP-100 (Ball Configurable Platform)	Unknown			Satcatalog.com website[124]	e.g. Stp-Sat2, Stp-Sat3, StpSat4 heritage
Momentus	Vigoride	USD 4.8M	1	USD 4.8M	Techcrunch.com website[125]	Advertised estimate prior to finished development.

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[123] http://www.aag.org/galleries/gisum_files/AlRahman.pdf
[124] https://satcatalog.com/datasheet/Ball%20Aerospace%20-%20BCP-100.pdf
[125] https://techcrunch.com/2019/04/24/momentus-seeks-up-to-25-million-as-it-inks-deals-to-transport-cargo-beyond-low-earth-orbit/

11.6.3.2 RFI campaign

An RFI (request for information) campaign was then started contacting some of the manufacturers listed above for more detailed information on the technical suitability of their platforms and a cost estimate. The results are shown in Table 47. Note that cost and schedule information are considered commercial in confidence and are provided in a commercial-in-confidence version of this report.

The technical consultation confirmed that for most COTS buses, the high data rates associated with the SCR mission represent a challenge that needs customisation of a COTS solution to be solved.

Table 47 RFI campaign results

Parameter	Procured element	Reference platform name	Non-compliances (to payload or mission requirements respectively)	Source
Berlin Space Technologies	Satellite bus	LEOS	☐ Georeferencing accuracy w/o post-processing (200-400m)	Supplier quote
	Mission	LEOS bus + Amos ELOIS Payload	☐ Georeferencing accuracy w/o post-processing (200-400m)	Supplier quote
Blue Canyon Technologies (Raytheon)	Satellite bus	XSat Mercury	☐ Downlink rate (50Mbps) ☐ On-board storage (64GB)	Supplier quote
Eartheye/ Satellogic	Mission	-	☐ Swath width (30km) ☐ Spectral bandwidth (9-24nm) ☐ Radiometric accuracy (3%-5%) ☐ Radiometric stability (0.5%)	Supplier quote
SSTL	Satellite bus	SSTL-MICRO	☐ Propulsion upgrade required	Supplier quote
York space systems	Satellite bus	S-Class	☐ Downlink rate (150Mbps)	Supplier quote

11.6.4 Australian technology readiness and development timeframes

A key element in providing the Australian Government with an operational capability both from a local and overseas supplier is a realistic assessment of current capabilities and an estimation of maturation timeframes. In a dedicated work package during the study the maturity of technology and team heritage was assessed for this purpose and the results are presented in the following sections.

11.6.4.1 Mission-critical technologies

The technologies to achieve the required performance for various subsystems of the SCR mission have been identified and assessed in a worldwide and Australian context. The basis for evaluation is the NASA TRL scale[126]. The results are captured in Table 48.

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[126] https://sbir.gsfc.nasa.gov/sites/default/files/2020_Appendex_A.pdf

Table 48 TRL and expected development for SCR-required technologies

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
Launch	Launcher	Launcher		Worldwide	TRL 9			
				AUS	TRL 4-6	TRL 8 by 2022	Gilmour Space	According to website
Ground	Data processors	Pre-0 stitch	CCSDS conform	Worldwide	TRL 9			
				AUS	TRL 9		ANGSTT	
		L0	CCSDS conform	Worldwide	TRL 9		Elecnor Deimos, DLR, Argans, RAL, S[&]T	
				AUS	TRL 4	TRL 8 by 2023	GA development (internal or contract)	
						TRL 8 by late 2021	LatConnect 60	Support for data processing
		L1		Worldwide	TRL 9		Elecnor Deimos, DLR, Argans, RAL, S[&]T	
				AUS	TRL 6	TRL 8 by 2023	GA development (internal or contract)	
						TRL 8 by 2024	LatConnect 60	Processing L0 to L1 of hyperspectral
		L2		Worldwide	TRL 9		Elecnor Deimos, DLR, Argans, RAL, S[&]T	
				AUS	TRL 9			
		L3		Worldwide	TRL 9		Elecnor Deimos, DLR, Argans, RAL, S[&]T	
				AUS	TRL 9			
	Data distribution	Data distribution		Worldwide	TRL 9		USGS, NASA	
				AUS	TRL 9		GA or AusCopHub	
				Worldwide	TRL 9		MDA	

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
	Mission Operations Centre (MOC)	Operations	Mission planning, spacecraft monitoring and control, instrument operations	AUS	TRL 7	TRL 8 by 2021 TRL 9 by 2022	Saber Astronautics	RSOC- Responsive Space Operations Centre
					TRL 9		LatConnect 60	Mission Operations Centre (MOC) and Data Processing support services
	Stations	Stations		Worldwide	TRL 9		GA existing assets	
				AUS	TRL 9		GA existing assets	
					TRL TBC		EOS SpaceLink	2 x Australian ground stations from 2024
Space	Payload	VSWIR	General hyperspectral	Worldwide	TRL 9 TRL 9 TRL 4 TRL 9	TRL 8 by 2022	Headwall Photonics HyperScout Hyperspace AMOS ELOIS	
			Full spec compatible	Worldwide	TRL 4-6		Ball CHPS spec TBC	Spectral range TBC
				AUS	TRL 4	TRL 6 by 2021	ANU	
		Internal calibration unit		Worldwide	TRL 5	TRL 8 by 2022 (12-18 months)		Components are COTS, but systems are custom built
	Platform	Avionics		Worldwide	TRL 9		SSTL	
		Platform control		AUS	TRL 6-8		Inovor UNSW	Unlikely to be suitable given the mission profile (rad-hardened etc), or have sufficient storage capabilities
					TRL TBC		SITAEL	Platform technologies provider

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
		Payload data handling		AUS	TRL 9		Myriota Inovor Fleet UNSW	Myriota - Autonomous operations including onboard processing
					TRL 6	TRL 8/9 by 2022	Spiral Blue	
		Electric Propulsion	>5kNs	Worldwide	TRL 8-9 TRL 8 TRL 7-8		Enpulsion EXOtrail PhaseFour	According to website According to website According to website
				AUS	TRL 3-4	TRL 6/7 by 2022	Neumann Space	(if applicable)
					TRL TBC		SITAEL	Hall Effect Thrusters
		Cold gas propulsion	>5kNs	Worldwide	TRL 5 (similar systems TRL 9)	TRL 8 by 2023 (to be developed alongside platform)	Moog Vacco	According to website. System design needs to be tailored for spacecraft. (Components are COTS, but systems are custom built.)
				AUS	TRL 5	TRL 8 by 2023 (to be developed alongside platform)	Components (valves, filters, etc.): most likely from Lee Company (international company). Regulators: most likely from international company System design & integration in Australia.	(if applicable) According to website. System design needs to be tailored for spacecraft. (Components are COTS, but systems are custom built.)
		PL downlink antenna	X-band	Worldwide	TRL 9			
				AUS	TRL 3	TRL 6 by 2022	Inovor, SkyKraft, CEA, EMSolutions, UNSW	
		X-band Tx	>300Mbps	Worldwide	TRL 9		General Dynamics	

Element	Sub-system	Item	Performance	Option	Current TRL	Expected TRL development	Example equipment / provider	Comment
				AUS	TRL 2	TRL 6 by 2022 (24-36 months)	Inovor Cingulan Space	No evidence of current development.
		ADCS Components	0.02deg control accuracy	Worldwide	TRL9		Blue Canyon Sinclair Orbital Bus systems: York Space, SSTL, Photon	Sizing and component integration is likely.
			ADCS	AUS	TRL 7 ADCS	TRL 8 by 2021	UNSW Inovor	Sizing changes required
			STR	AUS	TRL 4-5	TRL 8 by 2022	UNSW Inovor	
		EPS		Worldwide	9			
				AUS	2		UNSW Inovor	Existing EPS would not provide suitable power for this class.
AIT	Test facilities	TVAC		Worldwide	9			
				AUS	9		AITC	
		Shock and vibe		Worldwide	TRL 9			
				AUS	TRL 9		AusTest, VIPAC	Cleanliness needs improving
		Instrument calibration		Worldwide	TRL 9		NASA JPL, NASA Goddard, UK NPL	
				AUS	TRL 5-6	TRL 7 by 2023		Guess on development time for a trained team. No capability exists currently.

11.6.4.2 Team maturity and experience

In analogy to the TRL for hardware or software technology, another critical aspect when implementing an operational capability is the team experience and maturity. This is expressed on a similar 1 to 9 scale as technical TRL in Table 49.

From this assessment it is evident that in terms of team experience there is only a small gap between the Australian and worldwide capabilities.

Table 49 Team readiness levels for critical capabilities required for the SCR mission

Discipline	Option	Current TRL	Example organisations
FSW development	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Fleet, Inovor, Myriota, UNSW
System integration	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Inovor, Myriota, UNSW
System validation	Worldwide	TRL 9	Numerous
	AUS	TRL 8	Inovor, Myriota, UNSW
Operations	Worldwide	TRL 9	Numerous
	AUS	TRL 8-9	Optus, CSIRO, Fleet, Myriota, UNSW
Propulsion subsystem AIT	Worldwide	TRL 9	Numerous
	AUS	TRL ?	UNSW, UQ, DSTG, Gilmour Space
Internal calibration unit AIT	AUS	TRL 4	
ADCS Integration	Worldwide	TRL 9	Blue Canyon, Adcole Maryland
	AUS	TRL 7	Inovor, UNSW

11.6.5 Parametric cost estimation

To support the bottom-up costing of the SCR mission, a second approach was used to derive an estimate of the mission cost. In this approach, a parametric cost model developed by the Aerospace Corporation based on the Complexity-Based Risk Assessment (CoBRA) tool was utilised. The CoBRA analysis model uses a data set of 140 NASA led space missions over the period of two decades (1989 – 2012).[127] The complexity index of each space mission is a function of various technical and programmatic parameters of the missions such as spacecraft specifications, costs, development time, mass properties and operational status. The complexity index was calculated for all NASA led missions then graphed relative to the cost of the satellites that were successful, impaired, or suffered failure (shown in Figure 23). A regression analysis yielded an exponential relationship between the complexity index and the mission development cost. It is evident that all failed or impaired missions in the data set have been implemented with a cost below the regression curve, thus allowing to conclude that too low of a budget increases the risk of mission failure.

The application of this cost model to the Australian space context is limited. This is namely because the reference missions forming the basis for the cost model are developed, built, and operated in a NASA space engineering context. A calibration attempt has therefore been made to check the cost model's performance against recent, known, Australian space missions namely UNSW Canberra Space's M2 Pathfinder and M2 missions. This calibration exercise is described in section 11.6.5.1 below.

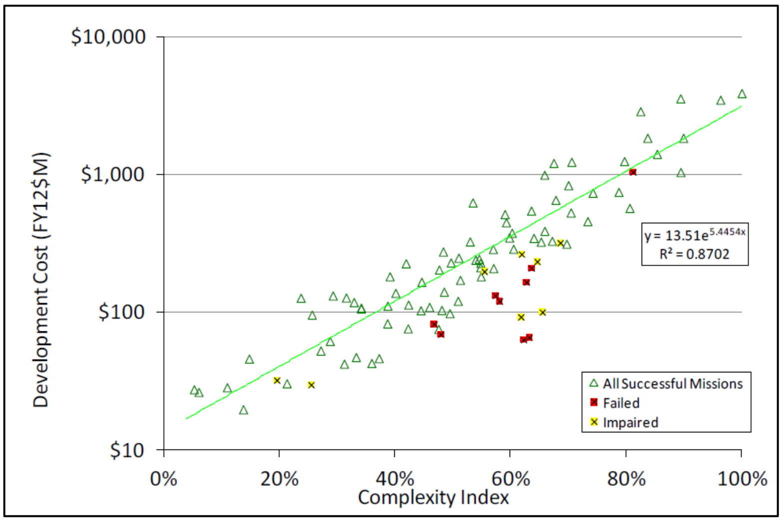

Figure 23 CoBRA complexity and cost relationship

It should be noted here that the CoBRA model could not be applied as designed because this requires the knowledge of the distribution of all reference mission performance values. The research literature only provides minimum, mean and maximum values of those distributions. As a work around, a uniform distribution was therefore assumed within the range between min and max values as has also been done in similar studies[128].

The regression equation produces results in FY2012 USD. These have been converted to FY2020 AUD by first adjusting to inflation according to data from the US Bureau of Labour Statistics[129] and

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[127] Yoshida, J. & Cowdin, M. & Mize, T. & Kellogg, R. & Bearden, D.. (2013). Complexity analysis of the cost effectiveness of PI-led NASA science missions. IEEE Aerospace Conference Proceedings. 1-14. 10.1109/AERO.2013.6496935.

[128] Veronica L. Foreman, Jacqueline Le Moigne and Olivier De Weck, A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions, AIAA SPACE 2016. AIAA 2016-5245. September 2016.

[129] https://www.usinflationcalculator.com/

then converted to AUD using data from the Australian Taxation Office[130]. The resulting conversion factor from FY2012 USD to FY2020 AUD is 1.75.

Employing the model as described to the SCR mission as far as currently designed and accounting for uncertainty in the various parameters yields a complexity index of 0.267 with an extreme-case uncertainty between 0.221 and 0.310. This corresponds to a mission cost estimate of AUD 83M with an uncertainty range between AUD 64M and AUD 105M.

Table 50 SCR mission technical parameters as input to CoBRA cost model

Parameter	Value	Unit	Uncertainty range
Redundancy	20		+30 | -10
Orbit	2		+2 | -2
Propulsion Type	5		+5 | -3
Design Life	24	months	+60 months | -24 months
Launch Margin	2	months	+2 months | -2 months
Solar Cell Type	2		+2 | -2
Pointing Knowledge	0.016667	deg	+0.042 deg | -0.017 deg
Battery Capacity	100	Wh	+120 Wh | -100 Wh
No. of Articulated Structures	1		+1 | -1
Thermal Type	0		+0 | -0
ADCS Type	3 axis stabilised, star tracker		
Data Volume	116	GB/day	+348 GB/day | -29 GB/day
Satellite Mass	35	kg	+57.6 kg | -27 kg
No. of payloads	2		+4 | -1
Radiation	20	krad	+60 krad | -12 krad
Delta-V	100	m/s	+200 m/s | -0 m/s
Data Storage Capacity	320	GB	+320 GB | -128 GB
PL mass	15	kg	+18 kg | -12 kg
Launch Mass	38.5	kg	+69.696 kg | -29.7 kg
Bus Dry Mass	20	kg	+30 kg | -15 kg
PL Data Rate	100000	kbps	+200000 kbps | -10000 kbps
S/C Heritage	40		+60 | -20
Orbit Average Power	43.225	W	+77.805 W | -15.12875 W
Battery Type	Li ion		+4 | -4
No. of deployed Struct	4		+6 | -2
Solar Array Config	Deployed fix		
Pointing Accuracy	0.016667	deg	+0.042 deg | -0.0017 deg
Uplink Data Rate	1	kbps	+11 kbps | -0.1 kbps
Flight SW reuse rate	50	%	+90 | -0
No. of thrusters	1		+4 | -0
Structure Material	Aluminium		

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[130] https://www.ato.gov.au/Tax-professionals/TP/Calendar-year-ending-31-December-2020/

Parameter	Value	Unit	Uncertainty range
EoL Power	123.5	W	+185.25 W | -61.75 W
BoL Power	130	W	+195 W | -65 W
PL avg Power	40	W	+52 W | -28 W
Foreign Partnership	Payload		
PL peak Power	100	W	+120 W | -50 W
Slew Rate	0.060683	deg/s	+0.121 deg/s | -0.061 deg/s

11.6.5.1 Calibration of cost model to Australian context

To provide a calibration reference for the CoBRA cost model applied to an Australian satellite mission, the results of the cost model have been compared to actual mission costs of two Australian missions. While this is not a scientifically sound method to derive an error value between the cost model results and an expected SCR mission cost, it does enable an assessment of the order of magnitude of the obtained cost figures.

The result of this exercise is summarized in Table 51. Details can be found in the commercial-in-confidence version of this report. The table shows the ratios between parametric and actual cost for the M2 Pathfinder and M2 missions as developed, built, and operated by UNSW Canberra Space. The values are significantly different with the uncertainty ranges not overlapping.

Table 51 Cost ratio between CoBRA model and actuals for 2 recent space missions

	M2 Pathfinder	M2
CoBRA cost / actual cost	10.5	2.87
Uncertainty range	7.5 – 16	2.2 – 4.4

This may be explained by the mission context of the M2 Pathfinder mission. It was implemented to de-risk many of the M2 subsystems and could thus benefit from some NRE efforts that had been previously performed and budgeted under the M2 mission cost. This way it was possible to implement the M2 Pathfinder mission for a relatively low actual cost. This allows the conclusion that the presented ratio for the M2 Pathfinder mission is likely too high.

A realistic figure for the ratio to transform CoBRA cost estimates to the Australian space context is likely to be found in the range between 2.5 and 5.

Applying this value to the parametric cost estimate of the SCR mission (AUD 83M) yields an adjusted Australian-context cost of AUD 16.6M to AUD 33.2M. This agrees with the bottom-up cost estimate as presented in chapter 10.

12 Recommendations and open points

The study makes the following recommendations:

1. The tendering process for the next steps of the SCR pathfinder missions should be initiated as rapidly as possible to have a realistic chance of operating the mission in cooperation with NASA's CLARREO Pathfinder mission.
2. The following satellite technologies can be simultaneously de-risked and developed to provide internationally competitive, Australian satellite subsystems because they currently do not exist on the commercial market:
   a. A hyperspectral instrument meeting all observation requirements as identified, including the facilities to assemble and integrate it.
   b. A micro-satellite on-board calibration subsystem for a hyperspectral payload to achieve radiometric stability of 0.2% over 30 days.
   c. A high-data rate payload data handling subsystem for micro-satellites capable of simultaneously reading and writing hyperspectral data streams.
   d. An X-band transmitter and antenna to achieve >250Mbps downlink data rate for a micro-satellite.
3. Explore the viability of a new ground station site in Antarctica, including undersea cable, as it would allow complexity on the spacecraft communications system to be reduced.
4. UNSW Canberra Space assesses the SCR mission is ready for phase A and B mission development analysis.

5. A phase A and B study could in parallel mature the specification of the relevant Australian-built satellite subsystems and thus further reduce the risk of the Australian industry content implementation pathway:
   a. A thermal control concept to ensure the stable operating environment for the hyperspectral payload to achieve the required radiometric stability.
   b. An ADCS subsystem capable of controlling the satellite as required
   c. An electric power subsystem providing the required power to the satellite

13 List of acronyms and abbreviations

Table 52 Abbreviations and acronyms

Abbreviation	Description / meaning
18 SPCS	18th Space Control Squadron
ACT	Australian Capital Territory
ADCS	Attitude determination and control subsystem
AGO	Australian Geospatial-Intelligence Organisation
AIT	Assembly, Integration, and Test
AIT	Assembly, integration, and test
AITC	Advanced Instrumentation Technology Centre
ANCDF	Australian National Concurrent Design Facility
ANGSTT	Australian National Ground Segment Technical Team (www.angstt.gov.au)
ANU	Australian National University
APEC	Asia-Pacific Economic Cooperation
ARD	Analysis-ready data
ASA/The Agency	Australian Space Agency
ASD	Australian Signals Directorate
ASDC	Australian Space Discovery Centre
AUD	Australian Dollar
AUS	Australian
AusCopHub	Copernicus Australasia Regional Data Hub (www.copernicus.gov.au)
BCT	Blue Canyon Technologies
BRMM	Buccaneer Risk Mitigation Mission
BST	Berlin Space Technologies
Cal/Val	Calibration and validation
CARD4L	CEOS Analysis Ready Data for Land
CC BY	Creative Commons, Attribution
CCSDS	Consultative Committee for Space Data Systems
CDF	Concurrent Design Facility
CEOS	Committee on Earth Observation Satellites
CLARREO	Climate Absolute Radiance and Refractivity Observatory
CNES	Centre national d'études spatiales
CoBRA	Complexity-based risk assessment
COG	Cloud Optimized GeoTIFF
CoM	Centre of mass
ConOps	Concept of operations
COTS	Commercial Off-the-Shelf
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSS	Coarse sun sensor
DSTG	Defence Science and Technology Group
DV	Delta-V (velocity increment)
EC	European Commission
EHS	Earth Horizon sensor

Abbreviation	Description / meaning
EM	Engineering Model
EMC	Electromagnetic compatibility
EO	Earth Observation
EPS	Electrical Power Subsystem
EQM	Engineering qualification model
ESA	European Space Agency
ESD	Electro-Static Discharge
FM	Flight Model
FOC	Full Operational Capability
FTE	Full-Time Equivalent
FWHM	Full-width half maximum
FY	Fiscal Year
G	Goal (for requirements)
GA	Geoscience Australia
GDP	Gross domestic product
GLAMR	Goddard Laser for Absolute Measurement of Radiance
GPS	Global Positioning System
GS	Ground station or ground segment
GSD	Ground sampling distance
GSE	Ground support equipment
HIS	Hyperspectral imager
Isp	Specific impulse
ITAR	International traffic in arms
KO	Kick-off
LED	Light emitting diode
LEO	Low Earth Orbit
LEOP	Launch and Early Orbit Phase
LGN	Landsat Ground Network
LSP	Launch service provider
LV	Launch Vehicle
MOC	Mission Operations Centre
MOI	Moments of inertia
N/A	Not applicable
NASA	National Aeronautics and Space Administration
NICSAT	National Intelligence Community Satellite
NPL	National Physical Laboratory
NSTF	National Space Test Facility
OBC	On-board computer
OGC WCS	Open Geospatial Consortium Web Coverage Service
PDR	Preliminary Design Review
PF	Pathfinder
PFM	Proto-flight model
PICS	Pseudo invariant calibration sites
PL	Payload
RAAN	Right ascension of the ascending node
RF	Radio frequency

Abbreviation	Description / meaning
RFI	Request for information
ROM	Rough order of magnitude
S/C	Spacecraft
SCR	Satellite Cross-Calibration Radiometer
SM	Structure model
SNR	Signal-to-noise ration
SSO	Sun-synchronous orbit
STAC	SpatioTemporal Asset Catalogs
STEM	Science, technology, and maths
STM	Structure and thermal model
SWIR	Short-Wave Infrared
T	Target (for requirements)
TBC	To be confirmed
TBD	To be determined
TIR	Thermal Infrared
TM	Thermal model
TOA	Top of atmosphere
TRL	Technology Readiness Level
TRUTHS	Traceable Radiometry Underpinning Terrestrial- and Helio- Studies
TT&C	Telemetry, Tracking, and Command
UK	United Kingdom
UNSW	University of New South Wales (Canberra)
US	United States
USAF	US Air Force
USD	US Dollar
USGS	United States Geological Survey
VNIR	Visible and Near-Infrared
VSSEC	Victorian Space Science Education Centre
VSWIR	Visible and short-wave infrared

14 Appendix A: Study participants

The list of experts involved in or consulted as part of the study is presented in Table 53.

Table 53 List of personnel involved in the study

Organisation	Person	Role / contacted for
AGO	Mathew Withheld	Study participant link to defence (DEF799)
ANU / AITC	Rob Sharp	Optical payload specialist
	Marta Yebra Jia Urnn Lee	OzFuel programme
Australian Space Agency	Aude Vignelles	Programmatic guidance
	Reece Biddiscombe Arvind Ramana	
	Kerrie Dougherty	Education/outreach expert
Berlin Space Technologies	Abdel Ismail Tom Segert	Business development Satellite bus provider
Blue Canyon Technologies	Ben Anderson	Satellite bus provider
CSIRO	Alex Held	AquaWatch programme
Eartheye	Nigel Conolly Shankar Sivaprakasam	EO imagery provider
EOS	James Prior Sarah Horne Laura Rodger Morgan Bryant Dr James Webb Dr James Bennett Michael Lachut Marshall Lewis Marcel Giermanski Alex Pollard Dejan Stevanovic Josh Vear Prateek Tachicherla	
Esper Satellites	Shoaib Iqbal	Hyperspectral smallsat and instrument provider
Geoscience Australia	Maree Wilson	Project Sponsor
	David Hudson Jonathon Ross	Customer point of contact
	Medhavy Thankappan	Cal/Val expert
	Vincent Rooke Roger Melton	Ground station experts
	Leo Lymburner Chris Penning Emma Luke	Earth observation experts
Gilmour Space	Peter Kinne Dr Aaron Pereira	Launch and bus provider
LatConnect 60	Venkat Pillay Rueben Rajasingam	Mission Operations Centre (MOC) provider and Data Processing support services
Myriota	Iain Cartwright	Mission design, capability delivery and domain expertise.
RocketLab New Zealand	Sandy Tirtey	Launch / satellite bus provider
SITAEL	Mark Ramsey	Satellite platform and key technology provider
SSTL	Alex da Silva Curiel Victoria Irwin Clive Oates	Satellite bus provider

Organisation	Person	Role / contacted for
Spiral Blue	James Buttenshaw	Payload data handling and mission technologies
Syrlinks	Guillaume Choain	Spacecraft communications subsystems provider
USGS (Inc. Aerospace Corporation and KBR)	Greg Stensaas (USGS) Cody Anderson (USGS) Grant Mah (USGS) Mark Adams (USGS) Steve Labahn (USGS) Steve Covington (Aerospace) John Clemenson (KBR) Simon Cantrell (KBR) Jon Christopherson (KBR) Scott Schramm (KBR) Bob Ryan (KBR)	Cal/Val, Ground Station, and Earth Observation Experts / Strategic Partners
UNSW Canberra Space	Denis Naughton Jai Vennik Igor Dimitrijevic Edwin Peters Anthony Kremor Sam Boland Russell Boyce Jan-Christian Meyer Courtney Bright Philippe Laniakea Vraj Patel	Mission design and domain expertise
York Space Systems	Melanie Preisser Benjamin Kron Mike Lajczok	Business development and technical support Satellite bus provider

15 Appendix B: Commercial-in-Confidence information and quotes

Information in this annex is considered commercial in confidence and was provided to Geoscience Australia and the Australian Space Agency only.

16 Appendix C: Ground station analysis

The amount of data generated is given by:

$$Data = t \cdot \frac{v}{GSD} \cdot B_{ADC} \cdot N_{Bands} \cdot N_{Across-track\ samples}$$

Where:

t is the number of seconds spent imaging per day (seconds/day).

v is the orbital velocity of the spacecraft (meters/seconds).

GSD is the ground sample distance (meters).

B_{ADC} is the number of bits used in the pixel digitiser (bits/pixel).

N_{Bands} is the number of bands sampled by the detector (number).

$N_{Across-track\ samples}$ is the number of across-track pixels (number).

The CDF study identified the following requirements for the SCR and MM payload configurations:

- Imaging for 14,256 seconds/day, based on an imaging duty cycle of 16.5%.
- An orbit of 700 km, and thus an orbital velocity of ~7 km/s.
- 12 bits per pixel.
- 200 bands for SCR and 205 bands for the MMI

Based on the requirements set out above, the amount of raw data generated by the scientific payload is given in Table 34. This is the average amount of raw (uncompressed) data generated per day.

The analysis conducted in 11.5.3 suggests that a lossless compression ratio of 1.6:1 (raw : compressed) is attainable for this mission. The mission is assumed to be limited by downlink capacity and that the data compression subsystem satisfies any size, weight, and power (SWaP) constraints.

Data compression is essential to ensuring that the payload data downlink system requirements remain feasible. The SWaP and complexity of the radio subsystem will increase if data compression cannot be utilized or has a lower ratio than specified above. Only lossless compression techniques were considered, as lossy compression decreases the quality of the scientific output.

Link budget definition

The maximum data rate that can be supported over a communication channel depends on the physical parameters affecting the channel. The main contributor is the free space path loss, which is directly caused by the expansion of the radio waves as they propagate through space. The further a wave travels, the larger area is covered by the radio wave. This means, that an antenna collecting a fixed area of energy samples a lesser amount of the energy compared to what is transmitted. The energy received must be sufficiently higher than the thermal noise that is generated by the receiver front-end hardware to allow successful demodulation and recovery of the data. This is called the signal to noise ratio (SNR). To ensure that the signal received at the ground station is sufficiently high, parameters such as spacecraft transmit power, spacecraft transmit antenna size and type, receiver antenna size and type, data rate and coding rate can be tuned. The minimum data rate requirements are set in Table 35 and are based on the length of the communication passes for a selection of ground stations that are in use. In this section, we investigate combinations of spacecraft transmit antennas and power amplifiers that can satisfy the data rates.

The communication link SNR is computed using a so-called link budget, which accumulates all the gains and losses that affect the radio frequency (RF) link. This is given by:

$$SNR = P_{OUT} + G_{TX} - LOSS_{TX} - FSPL + G_{RX} - NOISE[dB]$$

where the values are in Decibel and

$$NOISE = 10\, log_{10}\, ktB$$

$$FSPL = 20\, log_{10} \frac{4\pi df}{c}$$

The fixed parameters in the link budget are defined in the Table 54. The transmitter antenna gain G_{TX}, transmitter power amplifier output P_{OUT}, and bandwidth B are variables that are tuned and selected in Section [Space-based architecture definition]. In the following, the signal to noise ratio will be normalized to the data rate, and will be presented in the form energy per bit to noise ratio (Eb/N0), where

$$Eb/N0 = SNR + SE$$

and SE is the spectral efficiency.

Table 54 Link budget parameters contains the parameters used in the link budget calculations. A receiver temperature of 21 deg Celsius is assumed, and the spectral efficiency is calculated based on a typical root raised cosine pulse shaping filter.

Table 54 Link budget parameters

Name and unit	Variable	Value
Frequency [GHz]	f	8.1
Implementation losses [dB] **Cable and pointing, assumed**	$LOSS_{TX} + LOSS_{RX}$	7
Receive antenna gain [dBi]	G_{RX}	54
Noise temperature [K]	t	294.15
Noise power [dBm/Hz]	$NOISE = kt$	-174
Spectral efficiency [bits/s/Hz]	SE	0.83
Minimum Eb/N0 [dB]		5
Speed of light in vacuum	c	3E8

Ground-based infrastructure

Multiple ground stations are required to enable the effective operation and use of the spacecraft, and to satisfy the data downlink requirements identified. Multiple ground station configurations that satisfy the requirements are explored below. Figure 24 shows the locations of possible ground stations to support the SCR mission. In general, existing Geoscience Australia and partner assets can be utilized to satisfy the lower tiers (small swath width and large GSD) of the data budget. Higher tiers (large swath width and small GSD) are feasible only with larger ground station networks, or by utilizing lower TRL RF and optical technologies.

Orbit simulations were conducted using an orbit altitude of 700 km, for a satellite in a sun synchronous orbit (SSO).

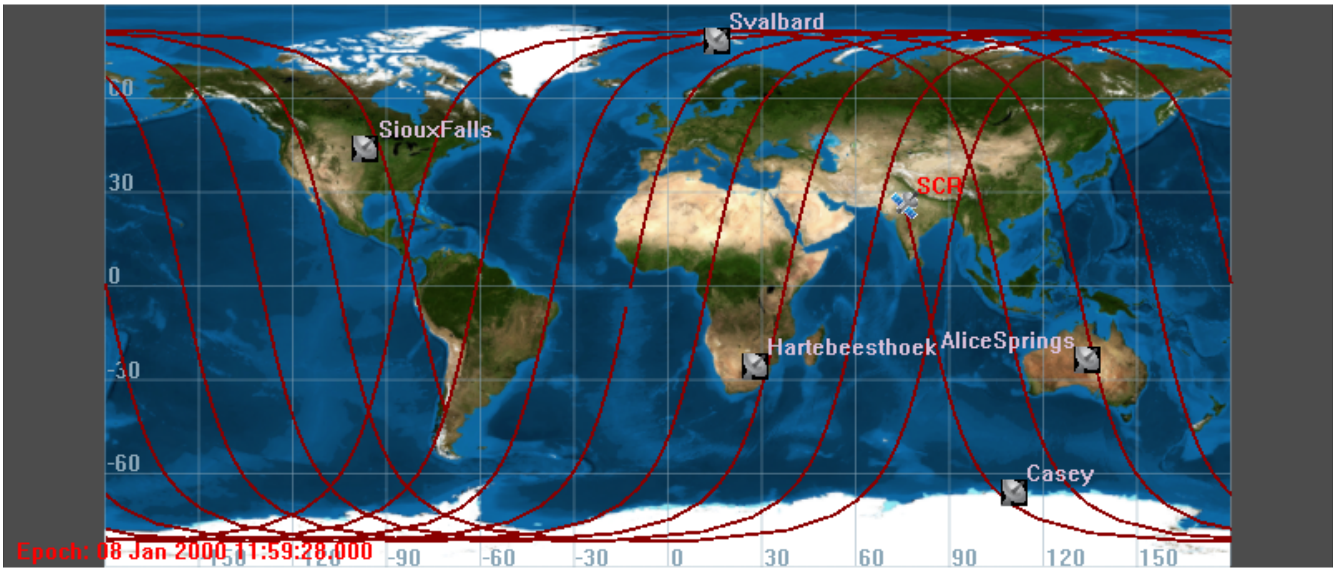

Figure 24 Prospective ground station locations

Effect of follower concept on ground station availability

If the SCR mission is to use the 'follower' concept, where it trails the target mission, the communication with the ground stations must be planned carefully, since both the target mission and the SCR will be in view of the ground station at the same time. This can be addressed in multiple ways. For example:

- The SCR mission trails the target mission by at least 15 minutes, which allows a full communication pass with both the target mission and the SCR and allows time for the antennas to re-target
- With ground stations that feature multiple 9 metre antennas, one antenna can be allocated for the target mission while the other is allocated for the SCR mission. Care must be taken with interference between the downlink of the two satellites. This can however be addressed by selecting appropriate frequency bands and sufficiently narrow beamwidth antennas.
- Pass-slicing between the target and SCR satellites is possible, but the data downlink data rate of the SCR mission must be proportionally higher since the communication window shortens. Further investigations into whether the target missions are affected by fewer downlink passes are required.

Prospective ground stations

Alice Springs, Northern Territory, Australia

Location: -23.758, 133.882

Alice Springs has two 9m parabolic antenna, capable of X-band and Ka-band downlink. The site is connected into Geoscience' Australia existing data network and has access to a command-and-control network for scheduling purposes. The site has S-band capability which could be used for TT&C.

The antenna is in-use for approximately 500 minutes per day per antenna (34% utilisation), based on a conservative communication schedule for the Alice Springs ground station.

There is no optical downlink capability installed.

Sioux Falls, South Dakota, USA (SF/USGS/EROS)

Location: 43.735, -96.625

Sioux Falls has a 10m parabolic antenna, capable of X-band. S-band transmit and receive for TT&C purposes is also available. The site has good internet backbone connectivity and could be linked to an Australian data storage site via an internet backbone. The Earth Resources Observation and Science (EROS) arm of USGS host and operate the ground station.

There is no optical downlink capability installed.

Hartebeesthoek, South Africa (SANSA)

Location: -25.890, 27.685

South African National Space Agency (SANSA) operate a large ground station network in Hartebeesthoek, consisting of around 70 antennae. Some suitable antennas include:

- HBK-5: 10m parabolic antenna with X-band receive capability (G/T = 31.0 dB/K[131]).

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[131] https://www.sansa.org.za/products-services/space-operations-2-2/

- HBK-8: 13.2m parabolic antenna with Ka-band receive capability (G/T = 41.8 dB/K).
- HBK-9: 7.3m parabolic antenna with X-band receive capability.

The site also includes various S-band uplink and downlink capability. SANSA assets can be accessed commercially or via a partnership. There is no optical downlink capability installed.

Svalbard, Norway (KSAT)

Location: 78.230, 15.397

Kongsberg Satellite Services (KSAT) operate a large commercial ground station network, with many sites across the world. Of particular interest is the high-latitude site located in Svalbard, called the Svalbard Satellite Station.

Suitable antennas include:

- SG1: 11.3m parabolic antenna with X-band receive capability (G/T = 36.8 dB/K)[132].
- SG2: 11.3m parabolic antenna with X-band receive capability (G/T = 35.7 dB/K).
- SG3: 13m parabolic antenna with X-band receive capability (G/T = 37.8 dB/K).

The site also includes various S-band uplink and downlink capability. KSAT assets are accessed commercially. KSAT is currently trialling an optical ground station in partnership with TESAT, which aims to offer 10 Gbit/s downlink capability[133]. This capability is currently being trialled in Greece but may be offered at Svalbard if successful. It is not currently available commercially.

KSAT also offer S-band and X-band from Antarctica with a 7.3m parabolic antenna (G/T = 32 dB/K). Backhaul from this site is provided by a geostationary C-band link and is relatively constrained at 50 Mbps. When paired with Svalbard this station allows for two contact opportunities each orbit. This station would be better suited to TT&C, and not for payload data downlink.

Casey Station, Australian Antarctic Territory, Antarctica (AN)

Location: -66.282, 110.529

Casey Station is a candidate site for the installation of a new ground station. The Australian Bureau of Meteorology operate a 2.4m parabolic antenna at Casey Station[134] with L-band and X-band functionality, however it is unlikely to be suitable for the proposed SCR mission. Connectivity to Australia is by way of a 1.5 Mbps satellite link using C-band geostationary satellites. The uplink required to re-transmit the data collected from an SCR mission is many magnitudes greater, therefore this link is not considered a viable option.

An Antarctic station is only feasible if a high-speed (100-1000 Mbps) connection to mainland Australia can be made. A fibre optic submarine cable from Hobart is one possibility that could offer data high data-rates (Gbps-Tbps), although there are many challenges associated with such a project (for example, icebergs causing cable damage). A fibre optic link is likely to be expensive (AUD 100M’s) to install but could be shared between the many different stakeholders located in Antarctica, reducing the cost to an individual organisation or government.

Antarctica does not have any optical ground station at present but could be installed to build future capability.

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[132] 453-NENUG

[133] https://www.ksat.no/news/news-archive/2021/ksat-and-tesat-will-offer-groundbreaking-optical-downlink-as-a-service/

[134] http://www.angstt.gov.au/network

When paired with an Artic station, a site at Casey Station would provide two spacecraft contact opportunities per orbit (assuming an SSO orbit).

A third Australian site could be considered if uninterrupted downlink capability is required; similarly, a hot-spare in the USA would be required. Deselecting the hot spare will require a larger on-board data buffer, to account for the temporarily decreased downlink availability.

In-orbit relay

An in-orbit relay system was assumed to exist, for the purposes of examining future technologies and capabilities that may be useful for this mission.

The in-orbit relay network is assumed to provide high data-rate coverage for 50% of the orbit of the SCR satellite. The relay system is likely to be X-band, Ka-band, or optical. There are commercial optical communication products available with high TRLs that can be used to form gigabit links between LEO, MEO, and GEO spacecraft. It is assumed that the relay satellite/network of satellites has gigabit connectivity to a ground station with high availability, such that it does not limit the downlink capability of the SCR.

Space-based architecture definition

The payload data transmitter shall be capable of downlinking the required amount of data per day. Buffering this data on board the spacecraft (‘store and forward’ from the science payload) is assumed to be handled by a capable data storage system.

X-band is preferred over Ka-band and optical communications due to the availability of existing ground station assets and a higher availability of higher TRL COTS transmitters and amplifiers available on the market. Additionally, Ka-band and optical communications are heavily affected by cloud cover and moisture levels in the atmosphere, limiting reliable communications to locations that feature desert-like climates, such as the arctic and deserts. Since X-band is not affected by these conditions, ground station sites anywhere around the globe can be utilized for data downlinks, resulting in low-latency and reliable data downlinks, and smaller on-board data buffer requirements. While S-band downlinks could be used as an alternative and can be used in combination with X-band, the smaller wavelength of X-band allows high-gain antenna apertures to be utilized with smaller physical footprints compared to S-band.

In this section, we find spacecraft power amplifier and antenna combinations that can satisfy the data rate requirements from Table 35 based on the assumptions in Table 54 and Table 55 below. We first analytically investigate the maximum data rate that can be achieved for relevant combinations of antenna gain and power amplifier output power. Next, we present available COTS radio, power amplifier and antenna products that can meet the required data rates set in Table 34.

Table 55 Slant range, propagation loss and convolutional code rate parameters

Slant range	d	800 km	2500 km
Free space path loss [dB]	$FSPL$	168.68	178.58
Convolutional code rate		½ but can run lower such as 7/8	½

The data rate achieved over X-band depends on the aperture size at the ground and on the spacecraft, as well as on the RF power output at the spacecraft and error-coding scheme used. Ideally the raw data and code rate are variable and can be reconfigured in real-time throughout a ground station pass. This allows the downlink rate to be adjusted depending on the signal strength that is received at the ground station. The signal strength varies significantly compared to when a satellite is at high elevation to the ground station compared to low elevation. Further, the ability to reduce the effective data rate by adjusting code and/or raw data rate allows data to be downlinked to ground stations with smaller antenna apertures when access to the high data rate ground stations is limited. The numbers in this report are generated assuming large (≥ 9m parabolic) apertures at the ground stations.

Coding

When the received signal to noise ratio (SNR) is not sufficiently high, the chance for errors to occur in the data increases. An effective method to improve the chance of successful reception of data is to code the data. Typical coding schemes are convolutional coding, that operates on a stream and block coding, that appends a checksum to the data. Combinations of these can improve data recovery rates at low SNRs.

Using convolutional coding with k=1 n=2 code rate (half of the data is error coding), a BER of 10^-5 can be achieved at 4 dB Eb/N0. Adding Reed Solomon block codes on top of this allows a BER of 10^-5 to be achieved at 2 dB Eb/N0. See Figure 25 for a graphical view of the trade-off between coding, BER, and Eb/N0. Further improvements can be achieved using TURBO codes or LPDC codes. The numbers in this report assume convolutional coding, and thereby provide a lower bound on the effective data downlink rates that can be achieved.

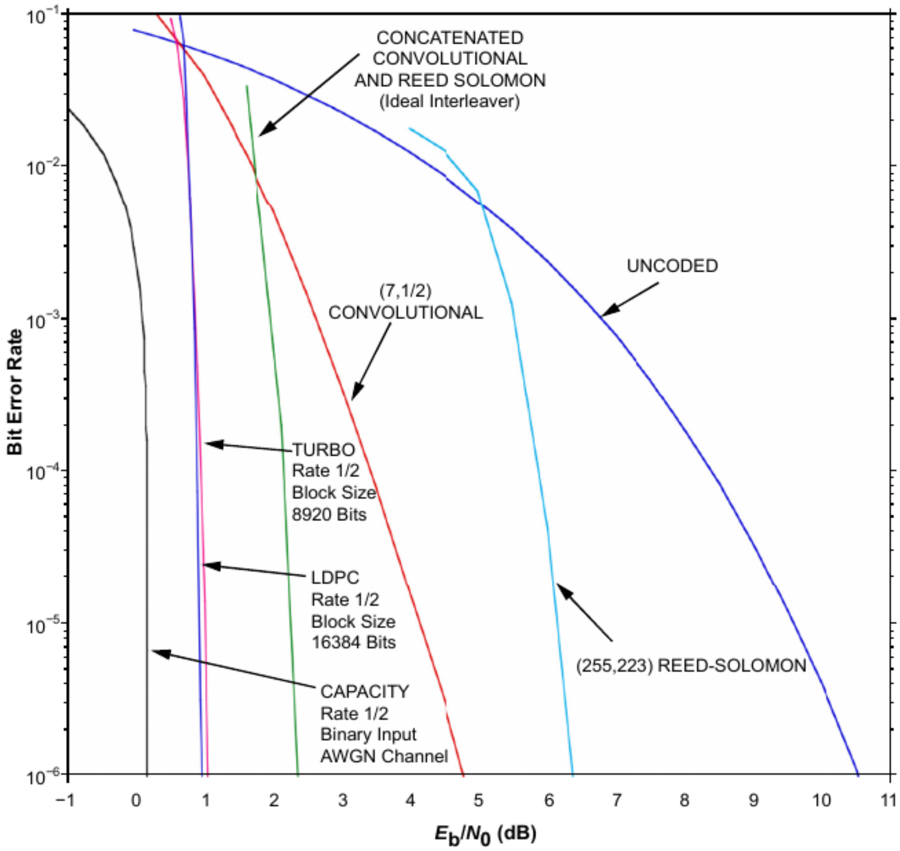

Figure 25 Bit error rates versus received signal strength for various coding schemes[135]

Assuming a rate ½ convolutional coding scheme, the effective attainable data rate at 5 dB Eb/N0 (10^-6 BER) for different power amplifier outputs can be computed and is shown in Figure 26. This data rate is computed at low elevation of 5 degrees (slant range of 2500 km for a 700 km orbit). When the slant range goes down as the satellite rises higher above the horizon, the signal power received at the ground station increases significantly (up to 12 dB in a 700 Km orbit). This allows to maintain a 10^-6 BER while reducing the FEC rate to ¾ or 7/8, thereby improving the effective data rate.

X-band radios options and link budget limits

Figure 26 shows the maximum theoretically achievable data rate when an Eb/N0 of 5 dB is desired for three different antenna configurations. The bounds are shown for 2500 km slant range (5-degree elevation) and 800 km slant range (60-degree elevation). It is worth noting, that at an elevation of 90 deg, the slant range would be 700 m. However, 90-degree passes do not occur frequently. The attainable data rates at closest approach are 10 times as high as at low elevation. While adjusting the code rate of the radio allows the effective data rate to be adjusted between 0.5 and 1, an Adaptive Coding and Modulation (ACM) radio needs to be utilized to take full advantage of the additional available link margin during the middle of high elevation communication passes. The bounds in Figure 26 are computed analytically from the link budget, using the parameters shown in Table 54 and Table 55. This is done by finding the bandwidth for which the link margin was 5 dB, and thus do not represent the Shannon limit. Thus, for a selected antenna, the more

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[135] https://public.ccsds.org/Pubs/130x1g3.pdf

power output of the RF power amplifier, the higher data rate can be achieved while maintaining the same energy per bit. The regions below the upper bound lines result in positive link margins.

The horizontal axis of Figure 26 shows different power amplifier output levels. The EIRP (Effective isotropic radiated power) of the system is then computed as $P_{out} + G_{ant}\ [dBm]$, where G_{ant} is the antenna gain listed in the legend.

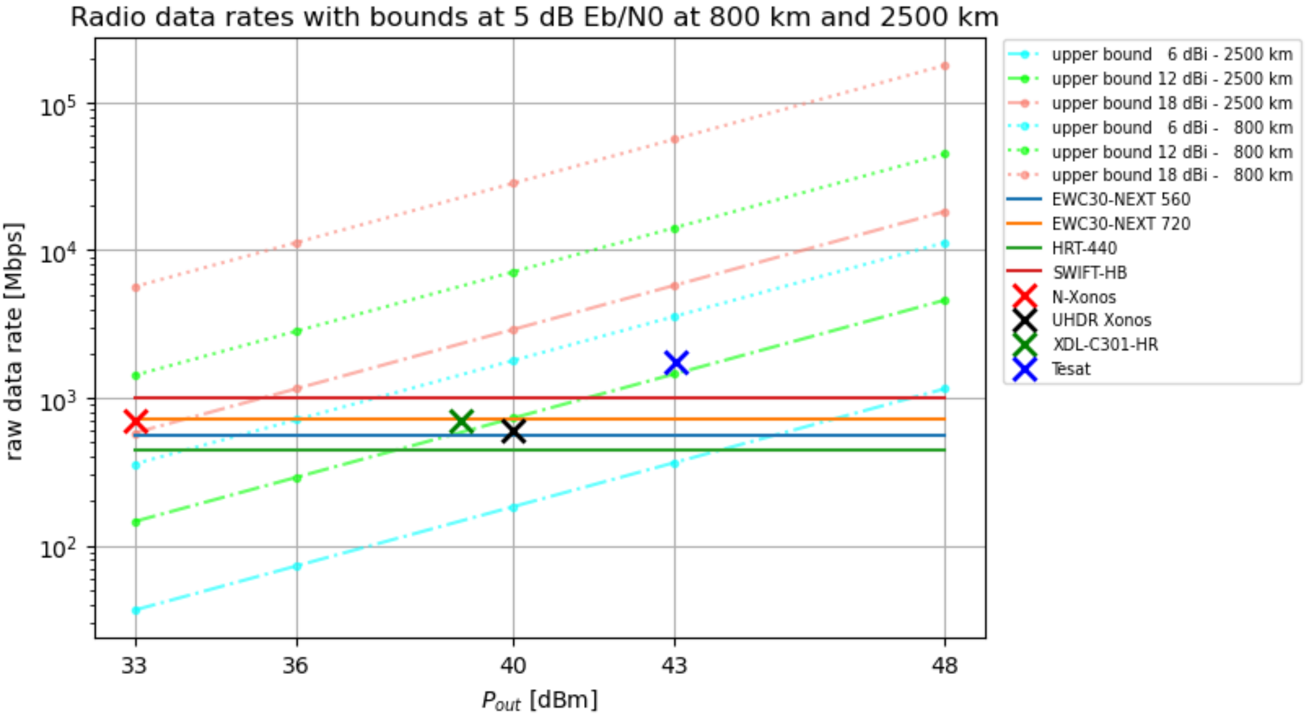

Figure 26 Bounds on raw data rates with multiple radio options

To use the graph in Figure 26, select the desired data rate, select an antenna gain, and then find the intersection with the upper bound for the desired slant range. Trace that intersection down to the horizontal axis. That is the minimum power amplifier output power that is required to sustain the desired data rate at 5 dB Eb/N0.

Multiple COTS X-band radio options are also indicated. The radios marked with crosses contain inbuilt power amplifiers. Thus, the output power is set, and the only variable to tune is the antenna selection. Any bound line that goes below the cross indicates that the maximum data rate cannot be achieved with the current antenna configuration. For example, with the Syrlinks UHDR-Xonos, a 5 dB Eb/N0 cannot be achieved at 2500 km slant range with a 6 or 12 dBi antenna. However, at 800 km slant range, even a 6 dBi antenna is sufficient to achieve a 5 dB Eb/N0.

The horizontal solid lines indicate the raw data rate of radios that do not include an inbuilt power amplifier. This allows a free selection of a power amplifier combination, and the selection of power amplifier gain can be traded of for antenna gain. Again, any upper bound lines that with the selection of power amplifier are below the solid line indicate a combination for which 5 dB Eb/N0 is not attainable.

X-band radio solutions

There are many X-band radios on the market. Table 56 lists key performance parameters for several radios that could be applicable for the SCR mission.

Table 56 X-band radio performance parameters

Name	**Syrlinks EWC30-NEXT**	**Syrlinks N-XONOS**	**Syrlinks UHDR Xonos**	**General Dynamics HRT-440**	**Honeywell XDL-C301-HR**	**Tethers SWIFT-HB**	**Tesat Integrated Data Downlink Transmitter**	**Custom built in house**
Life expectancy or TRL	7.5 years		6 years		6.5 years		7 years	
Max data rate	720 Mbps raw	350 Mbps effective	600 Mbps raw	440 Mbps raw (384 Mbps effective)	600 Mbps effective	Over 1 Gbps raw	1.3 Gbps effective	>1.3 Gbps effective
Modulation	8PSK	BPSK, QPSK, OQPSK, 8PSK	BPSK, QPSK, OQPSK, 8PSK, 16APSK (DVB-S2)	SQPSK	QPSK, 8PSK, 16APSK, 32APSK, 64APSK	BPSK, QPSK, OQPSK, 8PSK, 16APSK	QPSK, 8PSK, 16/32/64 APSK	Selectable
Power output		2 W	10 W	10 mW (need power amplifier)	8 W	Need power amplifier	20 W	Need power amplifier
Power draw during transmit		15 W	50 W	15 W	65 W		75 W	7 W
Coding	4D-TCM, convolutional 2/3 - 7/8	Convolutional ½, 4D TCM 5/6, Reed-Solomon	Convolutional, 4D-TCM, Reed-Solomon, DVB-S2	LDPC, Reed-Solomon, Convolutional	CCSSDS 131.2-B-1	Reed Solomon, convolutional, LDPC, BCH	SCCC	Selectable

Notes					ACM (adaptive coding) High reliability variant available		Supports ACM	Support ACM and/or variable bandwidth Based on FPGA + high speed direct to RF D/A converter such as AD9081
Link	Flyer	Flyer	Flyer	https://gdmissionsystems.com/products/communications/spaceborne-communications/mission-data-links/hrt-440-x-band-high-rate-transmitter	https://aerospace.honeywell.com/content/dam/aero/en-us/documents/learn/products/sensors/brochures/N61-2037-000-001_X-Band_HR_DownLink-br.pdf	https://www.tethers.com/software-defined-radios/	https://www.tesat.de/images/tesat/products/IDT_Data-Sheet.pdf	https://www.analog.com/en/products/ad9081.html#product-overview

X-band power amplifier options

Multiple COTS solid state power amplifiers are available on the market. Table 57 lists key performance parameters for several power amplifier candidates. The power added efficiency (PAE) of most of these range between 25% - 50%. The PAE is the output power measured as a fraction of the supplied power to the amplifier. The remaining power is transformed into heat.

Table 57 X-band power amplifier performance parameters

Name	**Qorvo TGA2700**	**Qorvo TGA2701**	**Qorvo QPA2612**	**Qorvo TGA2238**	**Qorvo TGA2752-SM**	**ERF-XBPA-0001**	**General Dynamics Spaceborne X-Band Solid State Power Amplifier**
Life expectancy or TRL							Used in Mars exploration rovers
Output power [dBm]	30	37	41	48	40	48	42
PAE	27%	42%	48% at 8.1 GHz	45% at 8.1 GHz	NA	NA	28%
Gain [dB]	25	21	34	31	28	NA	NA. input power +1 dBm
Notes	Chip only. Needs bias circuit design	Chip only. Needs bias circuit design End of life.	Chip only. Needs bias circuit design	Chip only. Needs bias circuit design	Chip only. Needs bias circuit design	Class AB	
Link	https://www.qorvo.com/products/p/TGA2700#documents	https://www.qorvo.com/products/p/TGA2701	https://www.qorvo.com/products/p/QPA2612	https://www.qorvo.com/products/p/TGA2238#documents	https://www.qorvo.com/products/p/TGA2752-SM	https://www.antaresdefencesystems.com/product-range/rf-amplifiers/	https://gdmissionsystems.com/products/communications/spaceborne-communications/mission-data-links/x-band-solid-state-power-amplifier

Qorvo has an extensive number of power amplifiers aimed at satellite communications available in their online catalogue.

Multi radio solutions

By taking advantage of right hand and left hand circularly polarized (RHCP and LHCP) antennas, two radios can transmit simultaneously on the same frequency band, effectively doubling the data rate. The receiving ground station needs to have both a RHCP and LHCP feed installed. Additionally, multiple radios can transmit in different frequency bands, which is like the operations concept of Landsat 7.

Antenna selection

Atypical antenna choice for X-band communications for small satellite form factors is the patch antenna. COTS patch antennas can be found with gains of 6-18 dBi. Generally, the higher the gain, the lower the half power beam width (HPBW). Additionally, waveguide pipe antennas with up to 9 dBi gain are commercially available. These are physically larger but tend to handle more power than a patch antenna. Table 58shows a few antennae configuration options.

Table 58 Antenna options

Name	**Anywaves X-band Payload Telemetry Antenna**	**Endurosat X-band Patch Antenna**	**Endurosat X-band Patch Antenna 2X2**	**Endurosat X-band Patch Antenna 4X4**	**RUAG X-band antennas**	**Endurosat custom**
Antenna type	Patch	Patch	Patch grid	Patch grid	Waveguide pipe	
Gain [dBi]	11	6	12	18	9	
Max power [W]	>3	4	4	4	?	> 20 W
Half power beam width [deg]	40	74	40	18	40-80	
Link	https://anywaves.eu/products/x-band-payload-telemetry-antenna/	https://www.endurosat.com/cubesat-store/cubesat-antennas/x-band-patch-antenna/#request-step-modal	https://www.endurosat.com/cubesat-store/cubesat-antennas/x-band-patch-antenna/#request-step-modal	https://www.endurosat.com/cubesat-store/cubesat-antennas/x-band-patch-antenna/#request-step-modal	https://www.ruag.com/en/products-services/space/electronics/antennas	Enquiry

If the spacecraft is imaging during a communication pass, and the communications antenna is pointing nadir, at 0 degrees elevation to the ground station, the spacecraft antenna angle will be 68 deg. Likewise when the satellite sets at 180 degrees at the end of the pass, the spacecraft antenna angle will be –68 deg. This means, that an antenna half power beam width of 136 deg is required to maintain a uniform antenna gain within 3dB throughout a communication pass. Depending on the gain pattern and roll-off, antennas can be placed such that the higher gain/narrow beamwidth antennas are used at low elevation, and the lower gain/higher beamwidth antennas are used at high elevation, where the free space path loss is significantly lower (10 dB) than at the horizon.

Several antenna configurations can be envisioned to achieve the needed link margins. .Multiple options are available to keep the ground station within the half power beamwidth of the spacecraft antenna while the spacecraft is imaging which include,:

- Use of a wide beamwidth patch antenna on the spacecraft.
    - Pro: Simplest design
    - Con: At most 6 dBi antenna gain can be achieved with COTS antennas. No single antenna can provide the 136 deg half power beam width required.
- Switch between multiple narrow beamwidth patch antennas
    - Pro: Simple software and hardware design. Higher gain antennas can be used.
    - Con: Coupling between the antennas needs to be investigated. RF switches at the antennas are single points of failure. If it is undesired that the satellite orients itself around the Z-axis (nadir pointing axis), the antennas must be placed such that there is a 360 deg view Nadir pointing.
- Beamform between multiple antennas
    - Pro: Multiple low gain antennas with wider beam widths can be used and combined to output increased power. An array of small monopole antennas can be used. Con: Complexity. Phase shifter circuits needed. The performance decreases significantly when transmitting at angles outside of the half power beamwidth of the low gain antennas. Patch antennas are not available with 136-degree beam width. On-board calibration and re-calibration are needed.
- Narrow beamwidth patch ona gimbal
    - Pro: One high gain antenna, low complexity RF design, GA experience operating mechanisms from Landsat 7
    - Con: Mechanical actuators and control required. Wear on RF cables and connectors due to gimbal movement. Complex development and actuators are a single point of failure.

Multi-antenna configurations can also be considered with switching that can provide at least 136 deg beam width:

- **5 X Endurosat X-band Patch Antenna** result is a 148 deg beam width with 360 deg nadir view. However only 6 dBi gain is achieved

- **5 X RUAG X-band Antenna**s can provide 9 dBi gain at up to 160 deg half power beam width with 360 deg nadir view.
- **20 X Endurosat X-band Patch Antenna 2X2 + Endurosat X-band Patch Antenna in the centre** max 154 deg beam width. The configuration will be the single patch in the middle, with the 2X2 arrays on each side. The 2X2 arrays can be adjusted such that the total half power beam width is 136 deg. In this case, the 2X2 array can be used until the satellite is at 36-degree elevation for a 700 km orbit, at which the slant range is less than 1100 km. This allows sufficient performance. However, to cover a 360 deg nadir view, 20 2X2 arrays are required.

Ka-band solutions

While Ka-band is the state of the art for large multimillion-dollar satellite missions, solutions for small satellites and cube satellites are still in their infancy. Advantages of Ka-band include the significantly reduced physical size of apertures needed on the ground and in space, and large spectrum-allocated bandwidths of up to 1.5 GHz. Challenges however involve requirements for increased pointing accuracy compared to X-band, weather, and humidity, which affect communications with ground stations in temperate climates, but work well in desert-like climates, such as the Arctic and Australian outback.

COTS Ka-band antennas are not widely available. But . Table 59 lists several candidates and their key performance parameters. However, Ka-band antennas can be designed and manufactured by Australian suppliers, such as EOS, CEA, or BEA.

Table 59 Ka-band radio performance parameters

Name	**Tethers SWIFT-HB**	**Micro Aerospace Solutions Ka band system**	**Astro digital 3rd generation**	**Tesat Gigabit modulator**
Life span expectancy or TRL				15 years
Max data rate	Over 1 Gbps raw	Up to 1 Gbps raw	320 Mbps – 1 Gbps effective	4 Gbps
Modulation	selectable	BPSK, QPSK	DVB-S2	Selectable
Power output	Need power amplifier	5W	0.6W + 23.5 dBi antenna	Need power amplifier
Power draw		20 W		30 W
Coding	selectable			Selectable
Notes	Information requested	Transmit frequency not in Australian spectrum allocation. Weight: 400 g	No information on website. Information requested.	
Link	https://www.tethers.com/software-defined-radios/	https://www.micro-a.net/communications_design-tmpl.html	https://www.ksat.no/globalassets/ksat/documents/ksat_white_paper.pdf	https://www.tesat.de/images/tesat/products/GMOD_Data-Sheet.pdf

Optical communication link options

Optical communication systems are a relatively new development for spacecraft, with few mature COTS optical terminals available on the market. Key advantages of optical communications include the ability to access high (10’s Gbps) data rates with lower attenuation, and lower power requirements than RF based solutions. .Disadvantages include the low TRL of available solutions and the more precise spacecraft pointing requirements, ground station support and the sensitivity of optical communications to weather and atmosphere moisture levels. Table 60 lists the status and performance parameters of optical terminals that are under development.

Table 60 Optical terminal performance parameters and development status

Name	**Hyperion CubeCat**	**Mynaric Hawk Air/Condor**	**Tesat TOSIRIS**	**Xenesis Xen-Hub**
Life span expectancy or TRL	TRL 8 (first flight 2022)	5-7 years (first flight 2021)	5 years	First flight 2021
Max data rate	Downlink: 1 Gbps Uplink: 200 kbps	1 Gbps 10-20 Gbps (based on press release, low reliability information)	10 Gbps	10 Gbps
Power draw during transmit	15 W		40 W	60 W (400 km orbit) 120 W (2000 km orbit)
Notes	Internal 64 GB data buffer	Did not respond to RFI		
Link			https://www.tesat.de/images/tesat/products/TOSIRIS_Data-Sheet.pdf	

Definition of selection criteria

In this section we provide several selection criteria on which we based the recommended spacecraft hardware configurations. The primary criteria which the solution must meet are the required data rate, a TRL that allows implementation within the programme schedule and reliability to achieve the minimum on-orbit lifetime for the mission.

Primary selection criteria

- Ability to meet the specified data rate.
    - Solutions meeting 80% of the minimum data rate requirement should be considered, as they may be viable with other system adjustments in areas such as imaging duty cycle or the number of bands samples.
- Technical Readiness Level
    - The risk tolerance (and thus required TRL) for the SCR and the MMI are likely to be different.
    - For a technical demonstrator, a TRL of 6 or greater is appropriate, otherwise weight should be given to selecting components with a TRL of 8 or greater.
    - Lower TRL subsystems may be considered on the SCR mission to raise the TRL of the subsystem for the MMI.
- Risk management and mission life-time
    - A first version SCR will be a Class D mission that tolerates more risk than a Class C mission envisioned for later versions of SCR and the MMI. Acceptance of these risk levels and the shortened mission life for a Class D mission (~I year lifetime) versus a Class C mission (1-3 year lifetime) need to be carefully considered.

    - Component selection and qualification campaigns are influenced by the designed mission lifetime.

Secondary selection criteria

- Thermal output of the spacecraft transmitter
    - If the thermal output of the transmitter is significant, then it may affect the workings of the payload, or may damage other aspects of the spacecraft. A cooling or heat transfer/damping system may be required to mitigate this effect. The addition of a cooling system increases spacecraft complexity, mass, volume, and cost.
- Ability to utilise Adaptive Coding and Modulation (ACM) or adaptive coding
    - ACM maximises the amount of data transmitted in each pass by adapting the modem characteristics to trade-off the received signal strength on the ground with the data rate.
    - ACM systems can add complexity as a backchannel is needed in addition to the payload radio, for the payload radio to be informed of the effectiveness of its selected mode. ACM can be run open-loop via estimation algorithms, but its performance is significantly reduced when compared to closed-loop operation.
    - Acquiring radios that support ACM is typically harder, as most high-TRL radios operate with a static configuration.

  - Since ACM maximizes the utilization of the link, the requirements of the power amplifier are lessened compared to non-ACM solutions, reducing the overall system power consumption and heat generation.

- Engineering and system complexity
  - A complex system is likely to incur greater validation and verification (V&V) costs than a simple system, or it may require additional redundancy to mitigate the risk added through complexity. The inclusion of redundancy itself can increase system complexity and thus risk, so this balance between complexity and redundancy must be carefully managed. However, Class C missions typically exclude redundancy. A more detailed analysis may reveal the need to designate future radiometer missions with a lower tolerance for risk classification than Class C.
- Subsystem delivery lead-time
  - The microsatellite market is heavily influenced by the “rapid access to space” ethos. Customers are realising the benefit of agile access to space by launching more missions sooner, with subsequent follow-ups, rather than waiting for one feature complete missions. The delivery time on externally sourced components can be a significant impediment to adopt this approach. For example, a 24-month spacecraft build, and AIT phase is heavily impacted if a core subsystem (such as the radio) has a lead-time of 12 months. Mitigations should be developed if this is foreseen to occur.
- Radiation susceptibility and tolerance
  - Components with no radiation tolerance will in general survive for shorter amounts of time than those that do, however qualified components are often more expensive.

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Pre-Phase A Study or the Australian Development of a Satellite Cross-Calibration Radiometer Series (SCR) Including Potential Support Partner Land Imaging Programs

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